Aalto-yliopisto
Aalto-universitetet
Aalto University

Master's Programme in Water and Environmental Engineering

Management of Excavated Soil in Infrastructure Construction Using Multi-Criteria Decision Analysis

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Master's Thesis 2021

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Title of thesis Management of Excavated Soil in Infrastructure Construction Using Multi-Criteria Decision Analysis

Programme Master's Programme in Water and Environmental Engineering

Major Water and Environmental Engineering

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Collaborative partner City of Espoo

Date 25.04.2021 **Number of pages** 45+ 01 **Language** English

Abstract

High volumes of excavated material being landfilled conflicts with the waste policy idea adopted by Finland to prioritize generation reduction, reuse and recover over landfilling. The objective of this study is to investigate the best choice of excavated soil management taking into consideration Espoo City's commitment to sustainable development while using Multi-criteria Decision Analysis and participatory decision. The study will compare the situation in Espoo in 2017 with two other scenarios simulating different stages of a transition from linear economy to circular economy.

The multicriteria decision analysis (MCDA) provides a parameter analysis to evaluate and clearly compare the presented alternatives. Soil is a key resource, but it is not yet specially highlighted in urban plans. The three alternative studied were: scenario S0, the current situation at the time of the study; scenario S1, to invest on the establishment of two temporary deposits enabling improving the reuse of gravel and high bearing capacity soil; scenario S2, seek to recycle 75% of all the excavated soil, with the implementation of more temporary deposits and/or new technologies to enable the reuse of all types of the excavated material.

The comparison of scenario results led to a recommendation that the city of Espoo should try to implement scenario S2. Scenarios S0 and S1 obtained similar score, but scenario S1 has the advantage of possibly functioning as a more realistic intermediate step to achieving the conditions in scenario S2 in the future. MCDA can be used as alternative way to improve the participation of city committees and help the participants to understand different points of view.

In the sensitivity analysis, the marginal utility contribution for every criterion was replaced by the extreme values 0 and 1 for all the scenarios consecutively. The biggest impact resulted of the criterion "Virgin Raw Material Demand" receiving the value 0 in scenario S2. In this case, scenarios S1 and S2 received quite similar scores and scenario S0 had a bit lower score.The comparison of the criterion values used in this study and obtained from literature indicate that it is unlikely that this criterion would behave like in the sensitivity analysis and changes in the inputs would most likely not have a big impact on the final result proportions.

Keywords MCDA; Soil Management; Circular Economy

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Preface

Firstly, I would like to thank my supervisor Harri Koivusalo and my advisor Pekka Pakkala for all the assistance and guidance with this master thesis. I also would like to thank Espoo City for the funding that allowed me to conduct this study.

I would like to say a special thanks to the professor Jaana Sorvari, who was my supervisor at the beginning of my thesis process, and to Virpi Nikulainen, who was always available to help and motivate me when I needed.

Finally, I would like to thank my family for the essential support I received during my studies in Finland. I want to specially mention my husband Janne Kivivirta, my mother Ana Matsuda and my mother-in-law Anneli Tupola, who were crucial in the challenging moments I faced during my studies.

This work is dedicated to my lovely daughters Johanna and Maria Paula.

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List of Abbreviations

CO2	Carbon dioxide emissions from transportation
DA	Decision Aiding
DM	decision-maker
EFD	Disposal of earth masses
EC	European Commission
EU	European Union
HBCS	high bearing capacity soil
HEL	Health Effects (Local)
HET	Health Effects (Transportation)
IC	Investment Costs
MCDA	Multi-criteria Decision Analysis
ODL	Other Disturbance Local
S0	Scenario 0
S1	Scenario 1
S2	Scenario 2
TC	Transportation Costs
TS	Percentage of soil treated
UN	United Nations
VRM	The need for virgin raw materials
YM	Ympäristöministeriö – Ministry of the Environment

1 Introduction

The current high volumes of excavated material going to final deposit conflicts with the waste policy idea of Finland to only resort to landfilling after trying to avoid generation and to reuse or to recover it as material or energy. (YM, n.d.)

The study will compare the situation of excavated soil management in Espoo in 2017 with two other scenarios simulating different stages of a transition from linear economy to closer to circular economy as exhibited in Figure 1. This transition seeks to maximize the reuse of the resources and reduce their depreciation, and it involves creating the necessary infrastructure for that to become possible.

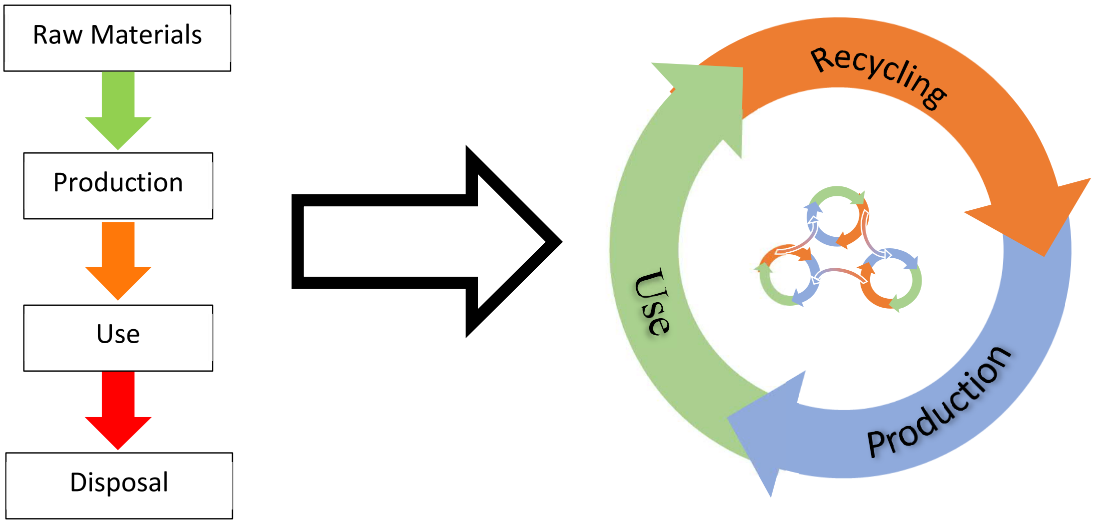

Figure 1. Transition from linear to circular economy.

Soil management incorporates diverse fields and divergent stakeholders, therefore multicriteria decision analysis is a good tool to help specially on the planning phases. It provides computational analysis to assess and systematically compare possible alternatives. For the analysis, the criteria were defined according to the most mentioned impact during preparation period. Unfortunately, some criteria could not be directly estimated, instead their variation was assessed using the proportional changes.

Soil is a key resource, but it is not yet specifically highlighted in urban plans. Moreover, when mentioned in the plans, they usually lack awareness of the flows, quantities and monitoring methods involved. It is important to create policies and prepare infrastructure to optimize the excavated material management, improve soil and rock reuse, hence reduce both cost and climate impact.

The objective of this study is to investigate the best choice of excavated soil management taking into consideration Espoo City's commitment to sustainable development, while using Multi-criteria Decision Analysis as a participatory approach. The main goal is to elaborate a recommendation about the best approach to handle excavated soil and rock to the city of Espoo by comparing three different scenarios. The first scenario reflects the circumstances in 2017, the second scenario represents the impact of the establishment of two temporary deposits enabling the reuse of gravel and high bearing capacity soil (HBCS). The last scenario is estimated to be the result of investments to reach a situation closer to the ideas of circular economy, with 75% of all excavated material being reused. (Espoo, 2021b)

2 Literature Review

This section pursues to provide a theoretical background for this study. It is divided in three parts, with the first two presenting the concepts of “Circular Economy” and “Multi-criteria Decision Analysis” and the final section focus on “Environmental Management” and how it can benefit from the two initially presented concepts.

2.1 Circular Economy

The European Union (EU) action plan for Circular Economy, published by the European Commission (2015), defines Circular Economy according to its goal to maintain for as long as possible the value of products, materials, and resources. Consequently, minimizing the generation of waste and supporting EU’s aspiration to achieve sustainable, low carbon, resource efficient and competitive economy.

As described by Breure et al. (2018), circular economy aims to maximize the reuse of resources and reduce their depreciation. This is not necessarily achieved within the lifespan of one product cycle. Breure et al. (2018) highlight that to get closer to the ideal circular economy, where no fresh resources are consumed nor waste is produced, a network organizational form combining different processes would be the best choice.

Circular economy is an important tool to achieve sustainable development. This goal, according to the United Nations (UN), can only be achieved if the actions taken to fulfil the needs of the present do not compromise the ability of future generations to meet their own needs. (World Commission on Environment and Development, 1987)

UN (2015) reinforced in the 2030 Agenda for Sustainable Development the idea that developed countries should take the lead on the development of scientific, technological, and innovative capacities. The 2030 Agenda also asserted that social and economic development are directly linked to the sustainable management of the natural resources within the planet. Therefore, it is essential to reduce waste generation and avoid the depletion of natural resources such as water and land.

The linear economy, where most natural resources follow a cradle-to-grave flow, reflects decades of easily available resources. The reality nowadays is different, and Lacy and Rutqvist (2015) listed some important changing moments that instigated the need for a change. The first was when the finite nature and increasing scarcity of non-renewable resources became evident, driven by a 50 percent growth in the demand for non-renewable resource in the period between 1980 and 2000, followed by an even higher growth of 80 percent in the following 14 years. The second was the acknowledgement of the rapid growth of already present stress on renewable resources. For example, the rate of groundwater depletion in the year 2000 was two times the rate in the year 1960 and by 2050, 4 billion people are expected to live in areas under severe water stress.

In circular economy, renewable material use is designed for reuse and ultimate return to the biosphere and non-renewable material use is designed to move back and forth between production and consumption with minimal loss in quality or value. The formation of topsoil, as well as its quality recovery are exceptionally slow processes and for that reason, Breure et al. (2018) stated that it can be considered a non-renewable resource. (Lacy and Rutqvist, 2015)

Resource scarcity is propelled by the current population growth, expansion of the middle class, and urbanization in combination with the fact that the potential to produce and consume new resources cannot grow endlessly. In this context, avoiding resource scarcity is an important ground to apply circular economy concepts in soil management. (Breure et al., 2018)

Another important issue that can be alleviated by adopting circular economy concepts is the disposal of resource residue in soil, water, and air. It is also valid to mention that an efficient use of resources in Europe can also be considered of political importance for improving the security of resource supply. (Breure et al., 2018)

Another direct consequence of the traditional linear model is the massive volume of waste generated. It is not only an environmental problem, but it also has social as well as economic impacts. Lacy and Rutqvist (2015) stated that waste translate into up to $1 trillion in annual lost value. To achieve sustainable development in a balanced and integrated manner, economic, social, and environmental dimensions should be taken into consideration. (UN, 2015)

To bring circular economy to reality it is necessary a long-term involvement in different levels. On the EU context, actions are needed from member states, regions and cities, businesses, and citizens. The idea is to create a framework for the management of natural capital as an asset. For example, one possibility is to create incentives for efficient use and management of land and soil, mineral resources, fossil fuels, water, and biodiversity. It is important to emphasize that waste management plays central role in circular economy and it should consider all waste. In terms of waste volume, one of the most significant sources of waste in the EU is the construction and demolition industry. (Breure et al., 2018; EC, 2015)

The EU action plan for the circular economy reinforces the concept of waste hierarchy, which outlines that the best option is to prevent the waste generation, followed by preparation for reuse, recycling and energy recovery. Disposal, such as landfilling, should be the last option, when any of the prior alternatives listed were not possible. (EC, 2015)

Soil and land play an important role in the efficient use of natural resources. They provide, for example, space for societal activities, store stocks of mineral resources, support the possibility of producing biobased resource to substitute the use of mineral resources, and are an important part of water and nutrients cycles. (Breure et al., 2018)

Transition to circular economy demands a systemic change, which includes targeted actions for each phase of the value chain and key sectors. Therefore, it is necessary to provide infrastructure and resources to create favorable conditions. Innovation is a vital part of the necessary changes, providing new technologies, processes, services, and business models to help rethinking ways of producing and consuming, to transform waste into value-added products. (EC, 2015)

The use of secondary raw material, which can be recycled and injected back into economy as raw material, needs to be fostered. A dynamic market for secondary raw material needs sufficient demand, incentives for the use of recycled materials, and optimal/multifunctional use of space (including temporary use of public space). (Breure et al., 2018; EC, 2015)

2.2 Multi-criteria Decision Analysis

Multiple criteria decision analysis (MCDA) is a type of Decision Aiding (DA) constituted of the following three basic elements: 1) a finite or infinite set of actions, 2) two or more criteria, and 3) at least one decision-maker (DM). It is a process to assist the acquisition of elements of response to questions made by a stakeholder in a decision process, making use of explicit but not necessarily completely formalized models. (Figueira et al., 2005)

The conference on “Multiple Criteria Decision Making” in 1972 marks the popularization of the concepts under the current name. But some of the ideas can be recognized much earlier. As reminded by Figueira et al. (2005), the link between decision making and the comparison of different points of view, in favor or against the action, were already present in texts from Ignatius of Loyola (1491-1556) and Benjamin Franklin (1706-1790).

Grounded on the three elements mentioned earlier, MCDA helps making decision by choosing, ranking, or sorting actions. Nonetheless, it is essential to be clear to everybody involved that the decision maker can behave on its own preferred way after the recommendation is made. (Figueira et al., 2005)

It is already uncommon to have one single clear criterion in decisions made by one single decision maker. In the case of multi-actor decision making process, it is extremely difficult to agree to one well-defined criterion acceptable by all. Different actors usually represent roles that reflect their own objectives and value system. When choosing multicriteria over mono criterion approach to decision making, it is less likely to neglect certain aspects of realism and to be limited to one particular value system as objective. Besides, considering more criteria enables a broad spectrum of points of view related to the actors involved and provides the discussion on the role each criterion should take on in the decision aiding process. (Figueira et al., 2005)

The decision aiding objective is to formulate propositions based on recognized scientific bases and with reference to working hypothesis. The final recommendations can be used to several purposes like: to analyze decision making context through the identification of actors, possibilities of action, their consequences, etc.; to increase coherence between the values underlying the objectives and the final decision; to help actors to cooperate by supporting better mutual comprehension and a framework favorable to debate; to elaborate recommendations using models and computational procedures prepared within the structure of a working hypothesis and; to participate in the legitimization of the final decision. (Figueira et al., 2005)

Potential action, Criterion/Family of criteria, and Problematic are the three concepts that normally guide the processes of structuring and analyzing of MCDA. Potential action is the target of the decision aiding, in other words, the object of the decision. Potential actions are not necessarily mutually exclusive and, in reality, there are several contexts that is preferable to select a kind of modelling that allow several potential actions to be implemented conjointly. On the other hand, many authors defend that potential actions should be mutually exclusive. In this case, when two different potential actions cannot be simultaneously put in operation, they can also be called alternatives. (Figueira et al., 2005)

An illustrative example given by Ishizaka and Nemery (2013) described the process being applied to the purchase of a new smartphone. The potential actions were 5 fictious products (SP1, …, SP5) and they were all evaluated according to the following criteria: price, customer reviews, screen size and storage size. The price criteria should be minimized and all the other maximized. Table 1 compiles the values defined to each potential action, according to every criterion after initial evaluation, final scores, and ranking. In this case the product SP3 had the highest score in the final process and was considered the best choice among the potential actions.

Table 1. MCDA applied to smartphone choice using price (P), customer review (CR), screen size (Sc.S) and storage size (St.S) as criteria. (modified from Ishizaka and Nemery 2013)

	P(€)	CR	Sc.S(in)	St.S(Gb)	Final Scores	Ranking
SP1	429	4	4.65	32	0.503	2
SP2	649	4	3.5	64	0.174	5
SP3	459	5	4.3	32	0.654	1
SP4	419	3.5	4.3	16	0.450	3
SP5	519	4.8	4.7	16	0.421	4

The set of potential actions is not necessarily fixed, it can be altered during the decision aiding process. The tool used to evaluate and enable comparison between potential actions from a well-defined point of view is called criterion. All potential actions must be compared regarding all criteria in a comprehensive way. The possible evaluations to which a criterion can lead are called degrees or scores of the scale. (Figueira et al., 2005)

Numbers, verbal statements, or pictograms can be used to represent the degrees of the scale of one criterion. The degrees used to depict the performance of the actions are used to compare them to each other. The scale of a criterion is a set that includes all the degrees, or scores mentioned earlier. The scale is called purely ordinal when the gap between two consecutive degrees does not have a real meaning on the preference choices. On the other hand, a quantitative scale is a numerical scale with degrees defined by a clear concrete quantity. In this case there is the absence of quantity (degree 0) and the presence of one unit, whose addition can be used to represent the difference between any two degrees of the scale. Therefore, the ratio between two degrees can have a meaning which is not exclusive of the two particular degrees. Some studies also use scales that cannot be considered any of the two mentioned types, for example interval scales that do not have a degree 0. (Figueira et al., 2005)

All criteria used should be understandable for each stakeholder and be considered a relevant way to compare potential actions without prejudging their relative importance. In addition, the set of all criteria together should satisfy some logical requirements, such as exhaustiveness, cohesiveness and, non-redundancy, to guarantee its coherence. It is important to remark that the mentioned requirements do not demand the criteria to be independent. Also, when two degrees are substantially close, they may not be enough to justify a preference between two actions. (Figueira et al., 2005)

The third concept, referred here as problematic, indicates the manner the decision aiding is conceived, i.e., what the decision aiding is trying to achieve. For example, the description problematic seeks to develop an appropriate set of potential actions, a proper family of criteria and use that to obtain performance values for the different actions according to the listed criteria in a merely informative way. (Figueira et al., 2005)

The other three types of problematics analyze or combine the different performances to obtain something. In the choice problematic, the goal is to select one single action, or a small group of choices. This can be done by choosing the most optimum action or simply eliminating as many choices as possible. The sorting problematic seeks to categorize the different actions in groups according to their performance in the used criteria. The objective of the ranking problematic is to classify and establish an order of preference between the potential actions. Three out of the four types of problematics listed above involve comparison between potential actions. Frequently, when comparing two or more potential actions, different actions have better performances in some of the criteria, and other actions in other criteria. To obtain a comprehensive judgement it is essential to aggregate the performance values in a clear objective way. (Figueira et al., 2005)

Multicriteria aggregation procedures are usually used to enable comparison between the different actions. It engages various inter-criteria parameters, like weights, scaling constants, aspiration, or rejection levels. They are used to define the role of each criterion in comparison to the others. It is essential to develop a logic of aggregation that takes into consideration the possible types of dependence that might be interesting to be used regarding the criteria and the circumstances that the difference between two performances is considered relevant, or not, when compared to the total possible range of performance. (Figueira et al., 2005)

The performance of a potential action according to one criterion is a real number. Consequently, the result of the aggregation procedure called global performance is also a real number. Depending on the problematic the potential actions can be compared using the performance of the different criteria or using the global performance. (Figueira et al., 2005)

Multi-attribute utility theory (MAUT) method is used in MCDA and it leans on the idea that decision makers seek to optimize a function to aggregate all the corresponding points of view related to the studied problem. The utility function is used to measure the desirability of the different alternatives. The different alternatives will receive a score for each criterion, called marginal utility contribution. These scores can be combined in different ways (for example with the use of weights) to compose the utility function. The values defined in the initial evaluation (like price in the example given previously in this section) are processed to obtain the marginal utility contributions in a way that the utility function will reflect the preferences of the decision maker. Figure 2 pictures how MAUT is used to rank different alternatives. (Ishizaka and Nemery 2013)

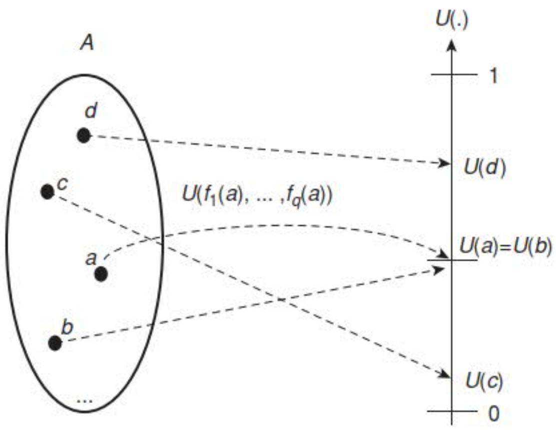

Figure 2. Representation of the ranking of the set A using the MAUT model, marginal utility contribution function f and utility score function U. (source: Ishizaka and Nemery 2013)

Multicriteria decision aiding is a good tool in the pursue for an efficient waste management. It might be used to rank different alternatives or help finding the optimal solution among different potential actions, taking into consideration different criteria and the complexity of the waste streams. (Achillas et al., 2013)

In the environmental field, decision making usually involves several stakeholders and conflicting views. It is a continuous and iterative process seeking to achieve acceptable compromises. Multicriteria decision analysis might, therefore, be applied to provide transparency and assist on the communication of individual preferences. A consensus is usually easier to be achieve when stakeholders clearly understand each other's views. (Marttunen, 2011; Mustajoki et al., 2004)

Construction industries have significant economic, technological and environmental impacts on a global scale. The increase of the produced construction and demolition waste, caused by rapid growth of this industry, in addition to higher social environmental consciousness, have evolved to an issue with inherent multiple factors and influences. These might be mutually conflicting, impeding the adoption of one single criteria for decision making. (Achillas et al., 2013; Banias et al., 2010)

2.3 Soil Management

In contradiction to the fact that several urban plans recognize the importance of soil as a key resource, there is little knowledge about soil material quantities and seldomly the plans incorporate indicators to enable measurement and monitoring of soil-related functions. (Magnusson et al., 2015; Teixeira da Silva et al., 2018)

The information on the fate and overall management practices of excavated soil and rock in urban areas is scarce. Currently the recycling rate of soil and rock materials is low and most of the material is directed to landfills. Therefore, there is a demand to assess the potential for increasing high value reuse, such as the use as construction material replacing natural aggregates. (Magnusson et al., 2015; Teixeira da Silva et al., 2018)

Urban areas are the source of around 80% of global CO_2 emissions. In rapidly growing cities a significant part of the urban areas has their main source of CO_2 emissions in the construction sector. This sector responds to 30% of total waste generation in the European Union. In addition, human population growth leads to an increase in the natural resources demand. Recycling of construction and demolition waste reduces landfilling and preserves natural aggregate resources, and thus recycling is mentioned in several environmental policies. Optimizing soil management will improve soil and rock reuse and consequently reduce both costs and climate impacts (Breure et al., 2018; Hiete et al., 2011; Magnusson et al., 2015)

The possible destinations of excavated soil and rock materials are the following: use on-site, use in other projects, use in other projects after pre-treatment, storage for later use, and use as landfill cover or dispose at landfill. The selected use depends mainly on how the system is prepared for and stimulates the reuse and the material physical properties. (Hiete et al., 2011; Magnusson et al., 2015)

Planning at an early phase is needed to achieve urban plans with better soil and rock management, for instance assessing demand and availability of excavated material. Changes are needed at all the decision levels from the construction project level (e.g. reuse on site) to regional authorities (e.g. establishment of policies and creation of infrastructure to be possible to store, sort, and process the material for later use). (Magnusson et al., 2015; Teixeira da Silva et al., 2018)

For the necessary changes to be achieved, it is imperative to spread the importance and the techniques of soil management to accomplish urban sustainable development. Circular economy is a good tool for that, once it aims at maximizing the reuse of resources and products and minimizing depreciation. Because most of the changes involve impacts on several fields and different stakeholders, multicriteria decision analysis is an attractive choice to assist especially on the planning phases. (Achillas et al., 2013; Breure et al., 2018; Magnusson et al., 2015; Teixeira da Silva et al., 2018)

Magnusson et al. (2015) noted that the information on available material geotechnical and geo-environmental properties, as well as the availabilities of recycling facilities, landfills and quarry materials are important parameters to management planning. The information should be used to analyze excavated soil and rock on a resource perspective, aiming at assessing the material recycling potential and its environmental benefits. In general, soil is not yet extensively contemplated in urban plans, not even in global leading cities. Teixeira da Silva et al. (2018) argued that this might change soon, once scientists have been putting effort to disseminate information and tools to enable the exchange of knowledge about the functions that soils provide to the several stakeholders.

Circular economy presents a framework to sustain efficient use and management of natural capital to secure its future provision. One of the challenges is the demand and supply relation, which is seldomly discussed in literature likely due to a fact that the supply is rather small when compared to the demand. This might change in the near future because of the development of new ideas and technologies propelling higher efficiency and capacity of material recycling. This trend might be especially strong in areas with expected population decline, where the demolition rates might overcome the quota of new projects. And it will bring even more controversy to a field that already involves several impacts and stakeholders. The multicriteria decision analysis approach supports a prosperous parameter analysis to evaluate and clearly compare the available alternatives. (Banias et al., 2010; Breure et al., 2018; Hiete et al., 2011)

Soil management importance is growing, and it has been researched in different ways in the past decade. For example, Banias et al. (2010) proposed a methodological framework using multicriteria analysis to find the optimal location for units of alternative construction and demolition waste management. Hiete et al. (2011) created an optimization model to understand the dynamics and planning of a construction and demolition waste recycling network as an integrated set of supply-and-demand chains at the regional level. Teixeira da Silva et al. (2018) addressed the importance of soil knowledge in urban planning by analyzing the role that soil related concepts had in urban plans and reports of world cities that included sustainability goals. In Finland, one example of integrating soil management to urban planning is the Absoils project, that demonstrated the use of abandoned and low-quality soils, such as clay and mud, in construction (Ollila et al., n.d.).

3 Site and Data Description

Espoo became officially a city in 1972. The city is located in the south of Finland and is surrounded by the Gulf of Finland and the cities of Helsinki, Vantaa, Nurmijärvi, Vihti and Kirkkonummi. As can be seen in Figure 3, the district of Kauniainen is located in the center of Espoo but it is an independent administration, and it is not part of the city of Espoo. (Espoo, 2021a)

The whole area of the city is 528 km^2, with 216 km^2 covered by water and the 312 km^2 being land area. In the end of 2019 Espoo had 289 731 inhabitants, 2.2% more than in the previous year. Considering only the land area, Espoo has approximately 930 inhabitants per km^2. Following the populational growth, 4297 new apartments were built in Espoo in 2019. (Espoo, 2021a)

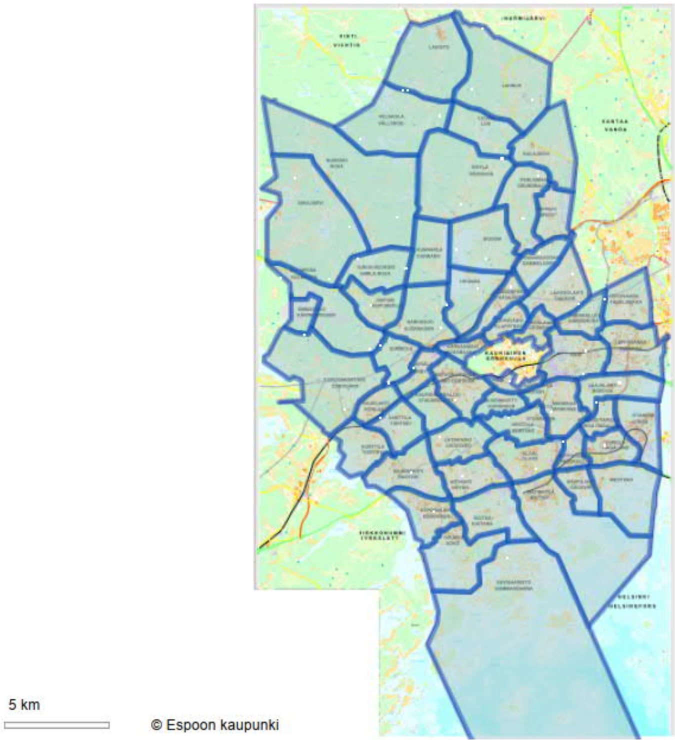

Figure 3. Map of Espoo City. (Source: Espoo, 2021c)

Administration in the Espoo City is divided into four sectors: The Mayor's Office, Education and Cultural Services, Social and Health Services, and Environment and Technical Services. They are advised and supervised by the city council, city board, committees, and boards. (Espoo, 2021a)

The City Council is formed by 75 members, chosen by election, and it holds the highest decision-making authority. There are 12 committees in Espoo, whose purpose is to organize and develop services in a resident- and customer-oriented way. They do the development by proposing definitions of policy concerning their own domain to the City board, which sometimes includes the decisions about surrounding infrastructure and soil management. They also manage the planning, the development and monitoring of operations, the economy, and the organization within the city. (Espoo, 2021a)

The Environmental and Technical Services department manages the landfilling of surplus masses of the city of Espoo. The main purpose is to guarantee operation condition for the construction industry by providing a destination for clean soil and rock masses that cannot be used elsewhere. Kulmakorpi deposit receives construction production materials from both private and the municipal sites in Espoo, Kauniainen and Kirkkonummi.

In 2017, 87% of the material was registered under private customers and 13% was from the cases where the customer was the city. The mentioned private majority also included city projects developed by private contractors once the material delivered might be registered, for example, under the transportation company, the general contractor, or the main contractor. The total amounts for the years 2015, 2016 and 2017 can be seen in Table 2 and the average distribution for this period is shown in Figure 4.

Table 2. Amount and distribution of material being delivered to Kulmakorpi between 2015 and 2017. (HBCS- high bearing capacity soil)

Year	Total m3	Gravel %	HBCS %	Clay %	Mud %
2015	724 910	17	27	47	9
2016	920 160	19	31	43	7
2017	1 102 450	18	21	52	9
Average	915 840	18	26	47	8

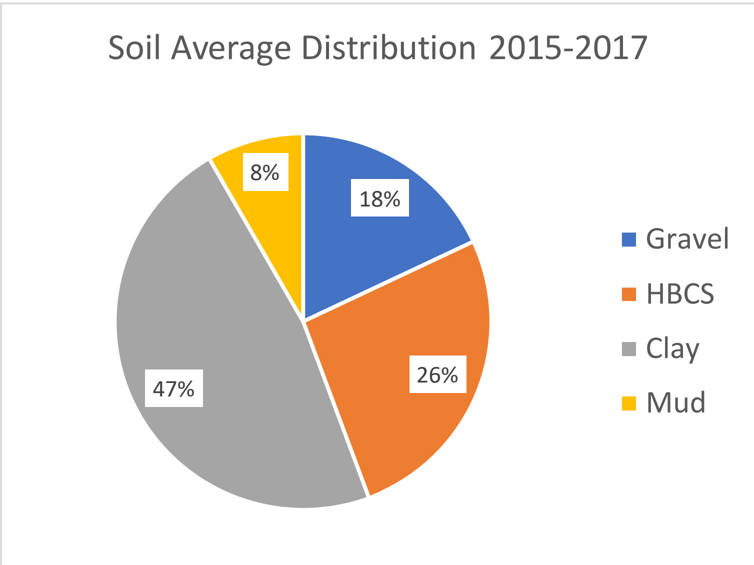

Figure 4. Average distribution of material being delivered to Kulmakorpi between 2015 and 2017.

The city of Espoo provided the majority of the data used for developing the different scenarios used in this study. The soil deposits operation was projected using management reports from Kulmakorpi and the study ordered by the city from Mapple Analytics Oy to estimate the impact of establishing two temporary soil deposit sites in Espoo (Mapple 2019).

Mapple (2019) used the registration of material delivered to Kulmakorpi during the period between May 2017 and September 2018. Using the address of origin and the traffic map of the city the study initially projected the distance travelled between the site and the deposit, travel time, CO_2 emission, and transportation cost. In a second phase, Kulmakorpi and two temporary deposits were considered, and the distances and corresponding parameters were recalculated connecting each site to the nearest collection point according to the travel time. Figure 5 shows the sites included in the study and the difference in the time travel between all material being transported to only one location or to the closest location among the three. Note that the temporary deposits are located in the areas with higher concentration of sites.

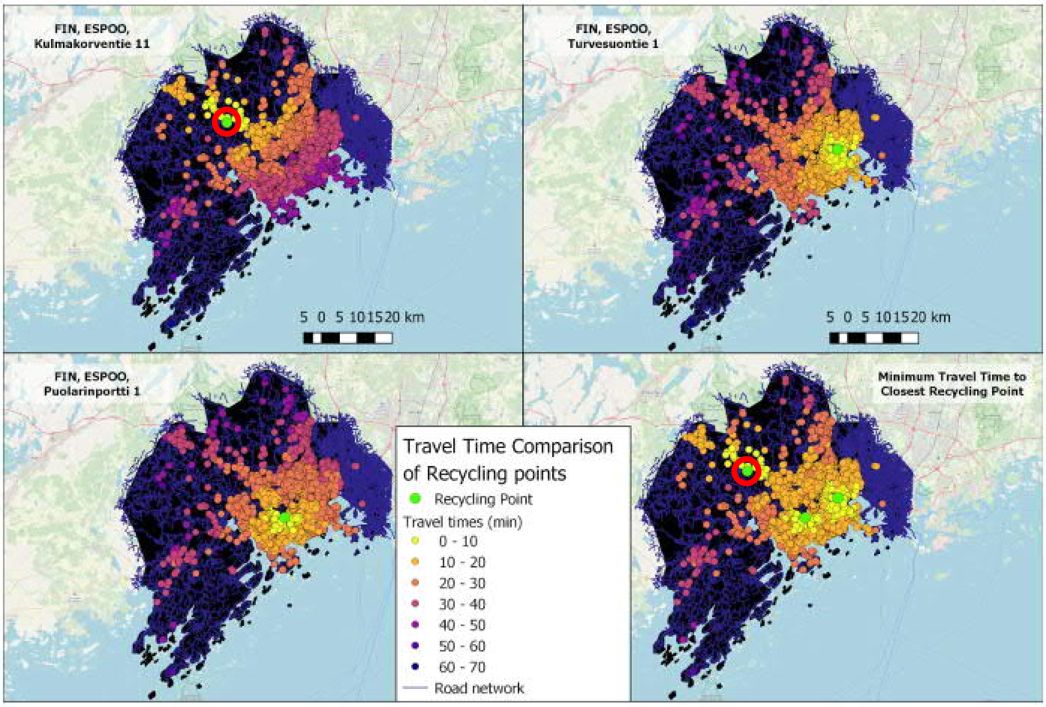

Figure 5. Travel time comparison in soil deposits transportation in Espoo. The final deposit location in the maps is highlighted with a red circle and the two temporary deposits are only marked with a green point. (modified from Mapple, 2019)

The soil demand was projected using the National truck traffic transportation distance statistics specific for the city of Espoo during the years 2015-2017, obtained from STAT (2018) and visible in Table 3.

Table 3. Domestic truck transport performance by transport distance, soil transportation, according to origin and destination in the period 2015-2017. (source: STAT 2018)

	OUT (t) (from Espoo)	IN(t) (to Espoo)	Espoo-Espoo(t)	
2015	1 306 750	1 245 000	2 350 000	
2016	1 434 225	1 701 000	2 101 000	
2017	1 705 384	935 000	2 865 000	
Total	4 446 359	3 881 000	7 316 000	
Average (t)	1 482 120	1 293 667	2 438 667	~956 547

4 Methods

4.1 Problem Definition

MCDA is applied to assist the soil management decision making for the city of Espoo. The question to be answered in the end of this analysis is: which of the potential actions is the best choice according to the criteria used in this study? MAUT is the aggregation method used, the utility function type used is additive and the weights were obtained through a questionnaire sent to several stakeholders.

The data used, as described in Section 3, is from October 2017 to September 2018. The performance of the scenarios was analyzed according to their economic, social, and environmental aspects, following the sustainable development concepts.

The tree of value was drawn to help defining the criteria that was used to analyze the scenarios. Figure 6 visualizes how each aspect is represented for different criteria, which enable comparing the main impacts caused by the different scenarios.

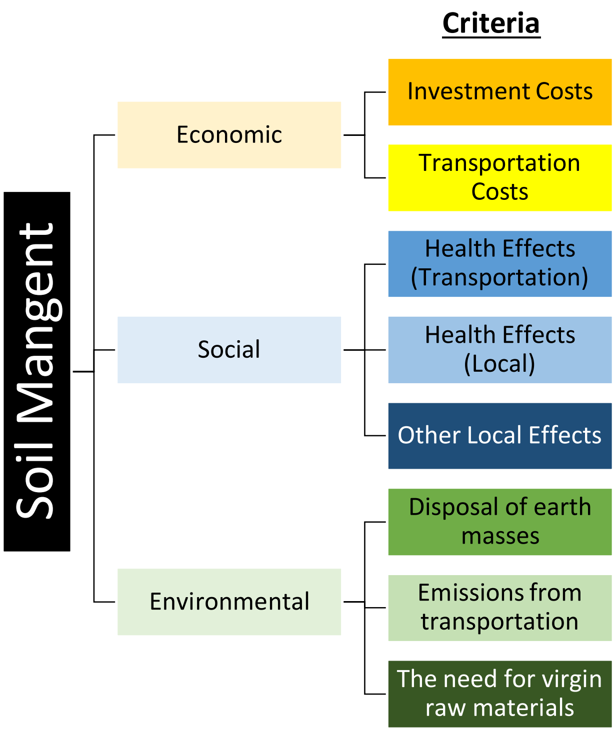

Figure 6. Tree of value illustrates the criteria used and information gathered according to their main aspects.

To analyze the economic aspects, this study used the costs linked to the soil transportation and investments needed for the necessary changes between current condition and the scenarios studied, measured in Euros.

Social aspects were represented by health effects caused by transportation, health effects caused by the installation of temporary support sites in residential areas, and other effects in the livelihood near the temporary sites. These criteria were the hardest to enable the comparison between the alternatives. The best way to proceed using the data available was to compare the variation of other phenomena that are proportional to the desired criteria.

The chosen criteria for the environmental performance were the direct disposal of earth masses into final destination, CO_2 emissions consequent from transportation, and the need for virgin raw soil materials for construction. The steps following this initial analysis can be checked in Figure 7. The initial evaluation of the scenarios involved defining values for two scenarios from the data collected and estimating the value for the third scenario based on the first two. These initial values were then transformed into performances as an intermediate stage to define the marginal utilities contributions, which were combined to the weigths, obtained from the questionnaire, to form the utility function and enable the comparison of the different alternatives.

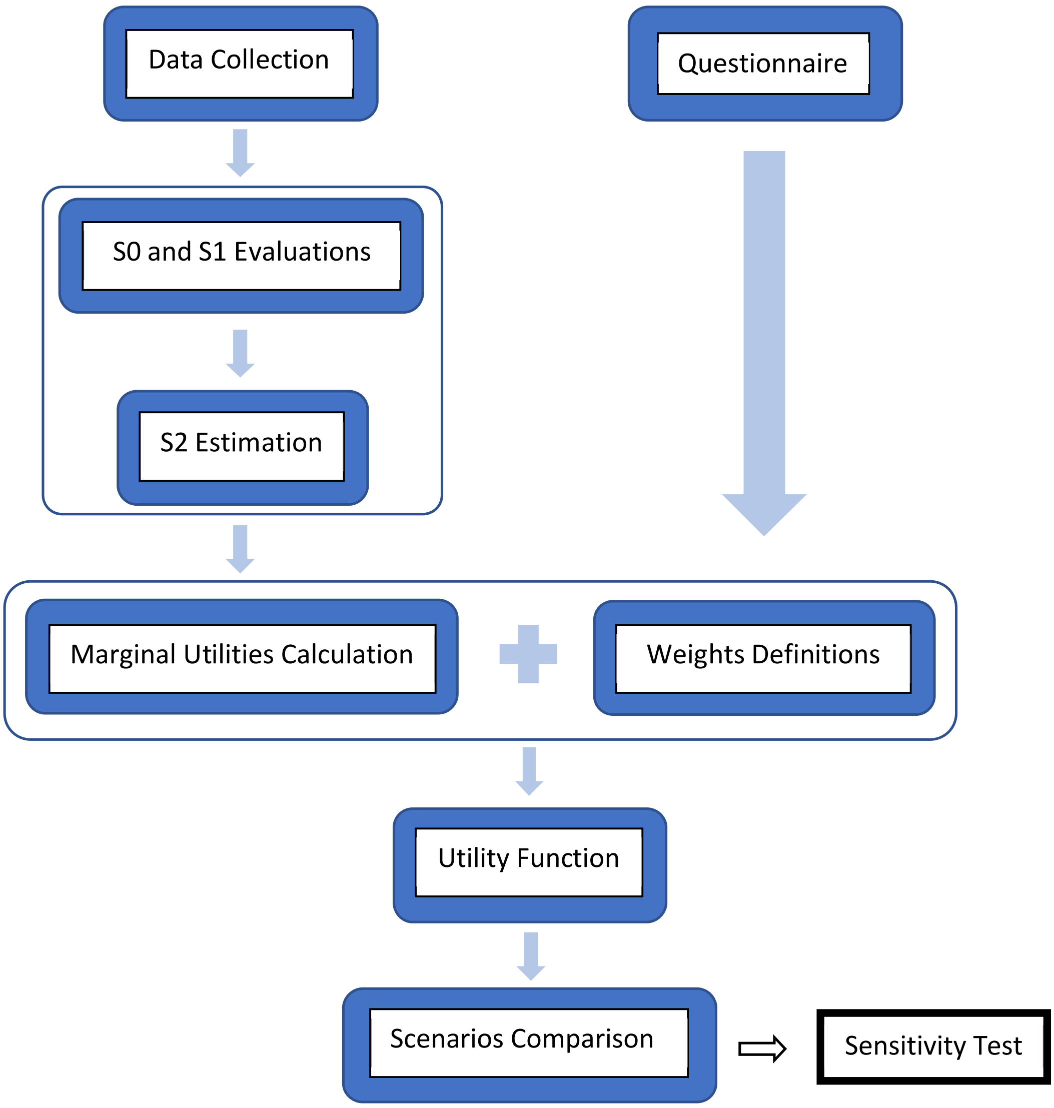

Figure 7. Research Steps.

The values obtained from Mapple (2019) reflected the loads calculated for the period between October 2017 and September 2018. The values are divided in two types, the values calculated directly from the data obtained from Kulmakorpi and the values estimated considering that part of the material was transported to a temporary deposit instead of being taken to final disposal The values of the amount of excavated soil delivered to final deposit, the total distance travelled, the time spent during transportation, the carbon dioxide emissions from the transportation and the transportation costs are summarized and listed in Table 4.

Table 4. Data obtained from Mapple (2019) used in the calculation of the evaluation of scenarios S0 and S1.

		Gravel	HBCS	Clay	Mud	Total
Amount (t)	Calculated	142 290	242 030	565 060	78 140	1 027 520
	Estimated	27 600	30 620	565 060	78 140	701 420
Distance (km)	Calculated	233 329	439 450	953 225	134 150	1 760 153
	Estimated	93 874	147 328	953 225	134 150	1 328 577
Travel time (min)	Calculated	416 967	782 646	1 700 831	242 005	3 142 449
	Estimated	208 456	333 863	1 700 831	242 005	2 485 154
CO2 emissions (t)	Calculated	300	566	1 227	173	2 265
	Estimated	121	190	1 227	173	1 710
Transportation Cost (€)	Calculated	962 482	1 812 730	3 932 053	553 369	7 260 633
	Estimated	387 232	607 729	3 932 053	553 369	5 480 382

Because in a first moment (scenario S1) only gravel and high bearing capacity soil would be re-used, there is no difference between the calculated and estimated values for clay and mud in Table 4.

The first step was to seek the value to enable comparison between scenario S0 and scenario S1. After that, these values were used to estimate the values for scenario S2.

The calculations in the following sections are based on the methods from Figueira et al. (2005), Borgonovo (2017) and Ishizaka and Nemery (2013).

4.2 Defining Potential Actions and Criteria.

Potential actions, in this study, are not possible to be simultaneously adopted, so they can be called alternatives.

4.2.1 Set of alternatives

Scenario S0 depictured the real situation for the period between October 2017 and September 2018. Most of the data used to evaluate this scenario was obtained directly from Table 4. It is possible that part of the material generated was reused in site or in other sites, but no registration of the reused masses was available. Therefore, in this study it was assumed that the amount of reused material was insignificant compared to the other existing flows and all excavated material was deposited in Kulmakorpi. A schematic representation of scenario S0 is shown in Figure 8 using only two construction sites, called projects as examples.

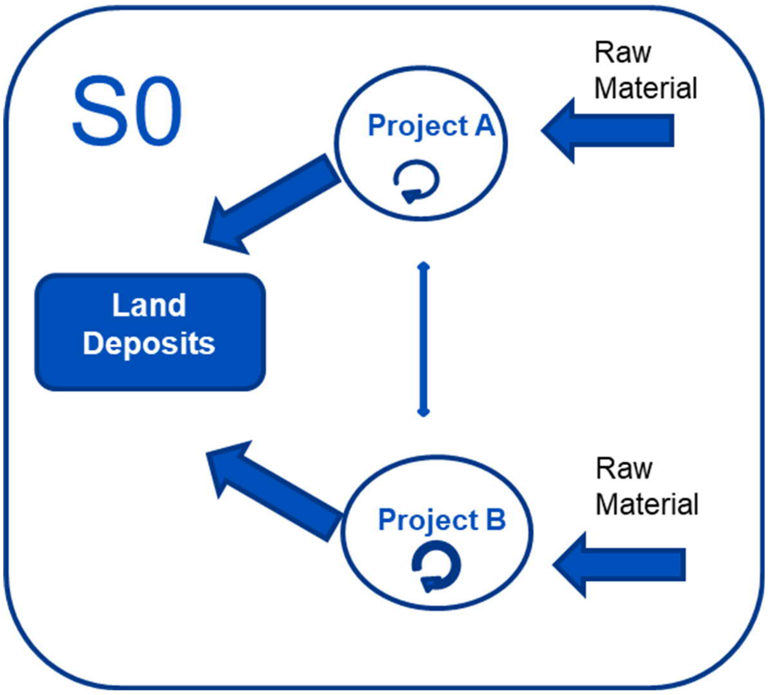

Figure 8. Schematic representation of scenario S0.

Scenario S1 was also estimated using data from Table 4. In this case, considering that part of the material was taken to two temporary deposits located in Puolarinportti 1 and Turvesuontie 1 to be reused. In scenario S1 only gravel and high bearing capacity soil was driven to reuse, in accordance with the current more likely reuse to be adopted in Finland. A schematic representation of this scenario is shown in Figure 9 using only two construction sites and one temporary deposit as example. In scenario S1, changes occur in the previously showed flows and three new flows are presented. The two-directions arrows display the flows between the projects and the temporary deposit and the unidirectional arrow leaving the temporary deposit represents the material stored and directed to other projects.

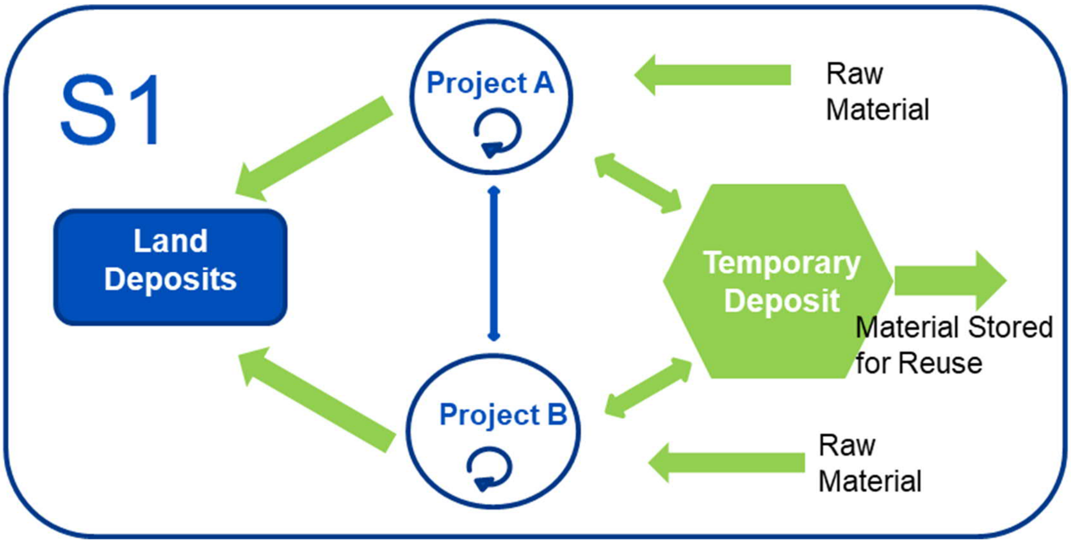

Figure 9. Schematic representation of scenario S1.

Scenario S2 was obtained through an extrapolation using the data from scenarios S0 and S1, to estimate the consequence of 75% of the material being reused. According to the average distribution, approximately half of the material delivered to Kulmakorpi was clay. Therefore, in scenario S2, it should also be reused. A schematic representation of this scenario is shown in Figure 10 using only two construction project sites and one recycling site as example. In this case, the flows leaving the recycling sites represent stored material and material treated to be reused.

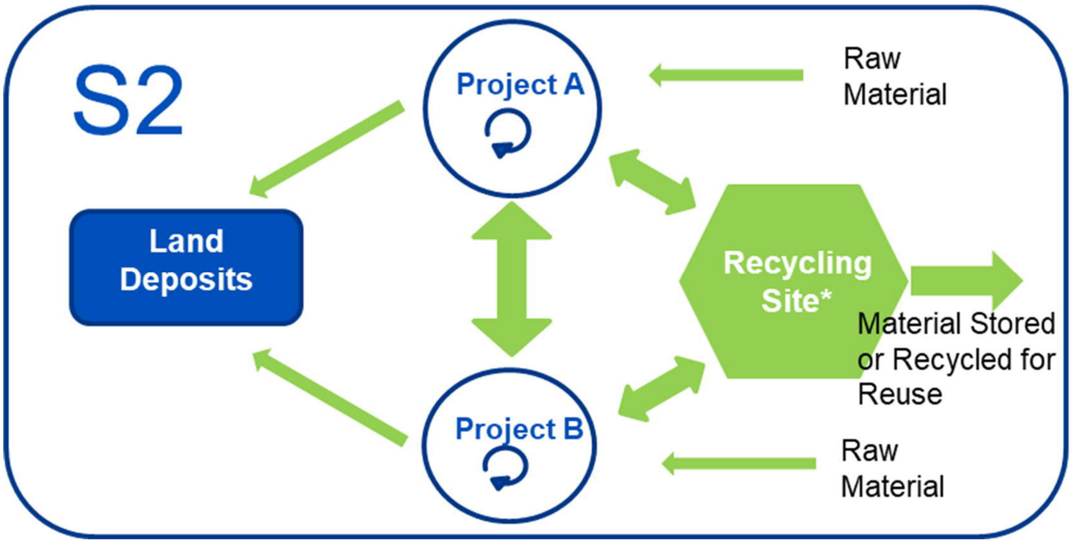

Figure 10. Schematic representation of scenario S2.

4.2.2 Set of criteria

Investment Costs (IC) criterion was used to compare the different scenarios from the economic point of view. It includes, for example, the costs of setting up a soil mass data coordination system, the costs of acquiring an interim storage area and the development and/or introduction of new technology. A set of assumptions listed in Table 5 was made based on market prices of similar activities/products.

Table 5. Assumptions used in the calculations.

Operational costs (final deposit)	1,5 €/t
Operational costs (temporary deposit)	2,5 €/t
Land annual rent	10 000 €
Coordinator annual cost	72 000 €
Machinery	30 000 €

Transportation costs (TC) criterion represents the total costs of transportation of the excavated material from the site to final deposit or temporary deposit. The values for S0 and S1 were obtained from Table 4.

Health effects – transportation (HET) criterion seeks to compare the noise and dust generated by the soil transportation in the different scenarios. These are directly proportional to the distance travelled. Therefore, its variation was estimated using the changes in the transportation distance in the different scenarios using the distance in scenario S0 as base for comparison.

For the Health Effects – Local (HEL) criterion, as in the previous case, the variations in noise and dust caused by material handling in temporary sites was also estimated using other parameter proportional to its variation. As shown in Figure 11, the parameter used was the percentage of soil being taken to final deposit. If less soil is taken to final deposit, it means more was handled in the temporary deposits and consequently more noise and dust was generated in residential area.

Figure 11. Noise and dust estimation concept.

Other Disturbance Local (ODL) criterion aims to evaluate other impacts in the neighborhood, social impacts rather than health issues. Examples of other impacts are changes in the landscape of a residential area and the impact on housing prices.

Disposal of earth masses (EFD) criterion represents the amount of excavated soil being directed to final deposit. If the land masses are disposed without being utilized, it causes material loss and permanent changes in the landscape.

Emissions from transportation (CO2) criterion display the total CO_2 emissions from transportation of the excavated material from the site to final deposit or temporary deposit.

The need for virgin raw materials (VRM) criterion represents the amount of natural aggregates brought to Espoo from other locations to fulfill the construction industry demand. Soil demand estimation was made using the data obtained from STAT (2018) that show how much soil in average was transported from other areas to Espoo. If the material is reused, the need for raw materials is reduced.

4.3 Scenarios Evaluation

In the evaluation phase, values were defined for the three alternative scenarios in two steps according to the different criteria presented in the previous section. Initially, scenario S0 and scenario S1 were evaluated using the initial data described in Section 3. In sequence, scenario S2 was estimated using the values obtained in the first step. The numeric values of a criteria ($C_{criterion,\ scenario}$) are represented by the abbreviations presented previously (Section 4.2). The evaluation values after the calculations are collected in Table 10.

4.3.1 S0 and S1 evaluation

The investment costs evaluations, $C_{IC,S0}$ and $C_{IC,S1}$, are constituted of operation costs, land rent, coordinator salary, and machinery purchase costs. The assumed values were obtained from Table 5. Further, Table 6 shows the costs gathered as the different types of operational costs and other costs and the total of the investment costs in the last column.

Table 6. Investment costs evaluations $C_{IC,S0}$ and $C_{IC,S1}$.

	Operational Cost Final Deposit (€)	Operational Cost Temporary Deposit (€)	Other costs (€)	$C_{IC,scenario}$ (€)
S0	1 541 280	0	0	1 541 280
S1	1 052 130	815 250	112 000	1 979 380

The values for the evaluation of the transportation costs, disposal of earth masses directly for final disposal and emissions from transportation were directly obtained from Table 4 and values are summarized in Table 7.

Table 7. Evaluations for scenarios S0 and S1 according to criteria TC, EFD and CO_2.

		TC (€)	EFD (m3)	CO_2 (t)
Calculated	Gravel	962 482	142 290	300
	HBCS	1 812 730	242 030	566
	Clay	3 932 053	565 060	1 227
	Mud	553 369	78 140	173
	$\boldsymbol{C_{criterion,S0}}$	**7 260 633**	**1 027 520**	**2 265**
Estimated	Gravel	387 232	27 600	121
	HBCS	607 729	30 620	190
	Clay	3 932 053	565 060	1 227
	Mud	553 369	78 140	173
	$\boldsymbol{C_{criterion,S1}}$	**5 480 382**	**701 420**	**1 710**

The criteria health effects – transportation (HET), health effects – local (HEL) and other disturbances caused by interim storage in the neighborhood (ODL) were evaluated through the variation of proportional phenomena. Their evaluation values are listed in Table 8.

It is important to mention that lower percentage of transportation distance was connected to lower health effects linked to the transportation. On the other hand, lower percentage of material being directed to final deposit was inversely proportional to the other two criteria, which means that less material going to final deposit, lead to more material being handled in the temporary deposits and causing higher impacts in the neighborhood. To define the values given to scenarios S0 and S2 according to the aforementioned criteria, Equation 1 was used. The base value (V_{base}) is the value of the phenomena linked to scenario S0 and scenario value ($V_{scenario}$) is the value for the phenomena in the scenario being analyzed. The data was obtained from Table 4.

$$C_{criterion,scenario}(\%) = \frac{V_{scenario}}{V_{base}} 100 \qquad (1)$$

Table 8. Evaluations for scenarios S0 and S1 according to criteria HET, HEL and ODL.

	HET	HEL	ODL
Proportional phenomena	Transportation Distance	Material being delivered to final deposits	
V_{base}	1 760 153	1 027 520	1 027 520
V_{S0}	1 760 153	1 027 520	1 027 520
V_{S1}	1 328 577	701 420	701 420
$C_{criterion,S0}$ (%)	100	100	100
$C_{criterion,S1}$ (%)	75	68	68

The need for virgin raw materials was estimated from the difference between the amount of aggregate being brought to Espoo and amount of material being handled in the temporary deposits and being available to be used as substitute of natural aggregate. In scenario S0 there was no material being handled in the temporary deposits, therefore the need for virgin raw materials $C_{VRM,S0}$ was estimated based on the amount of soil being transported to Espoo from other locations (1 293 667 t in Table 3). Assuming that 1 t soil takes 0,5 m^3, $C_{VRM,S0}$ was equal to 646 833.5 m^3. The amount of soil that was going to the temporary deposits was calculated from the difference of material going to final deposit in scenarios S0 and S1. The material handled in the temporary deposits in scenario S1, 326 100 m^3, was reinjected in the market and replaced part of the natural aggregates. The remaining demand $C_{VRM,S1}$ was equal to 320 734 m^3.

Finally, Table 9 lists the values defined for scenarios S0 and S1 that were used for the estimation of scenario S2.

Table 9. Scenarios S0 and S1 evaluation.

Criteria			Scenario S0	Scenario S1
Investment Costs	IC	€	1 541 280	1 979 380
Transportation Costs	TC	€	7 260 633	5 480 382
Health effects of transport	HET	%	100	75
Health Effects (Local)	HEL	%	100	68
Other disturbances caused by interim storage in the neighborhood	ODL	%	100	68
Disposal of earth masses directly for final disposal	EFD	m3	1027520	701 420
Emissions from transport (CO2)	CO2	t	2 265	1 710
The need for virgin raw materials	VRM	m3	646 834	320 734
Percentage of soil treated (%)	TS	%	0	32

4.3.2 S2 Scenario S2 Estimation

Equation 2 was used to estimate scenario S2 using linear regression. In this last scenario, 75% of generated excavated material was being reused, namely $P_{TS,S2}$ was equal to 75%. The percentage of soil treated ($P_{TS,scenario}$) of all scenarios and the evaluations of scenarios S0 and S1 were used in the calculation. The values for scenarios S0 and S1 were obtained from Table 9.

$$C_{criterion,S2} = max\begin{cases} 0.01C_{criterion,S0}; \\ \frac{[P_{TS,S2}-P_{TS,S0}]}{[P_{TS,S1}-P_{TS,S0}]}[C_{criterion,S1} - C_{criterion,S0}] + C_{criterion,S0}. \end{cases} \quad (2)$$

The same process was repeated to all criteria and the process of using linear regression to estimate scenario S2 is visualized in Figure 12. In the case of linear regression leading to negative values in criteria that cannot be negative, it was assumed that the function followed the linear regression until criteria evaluation was close to zero and from that point on remained constant.

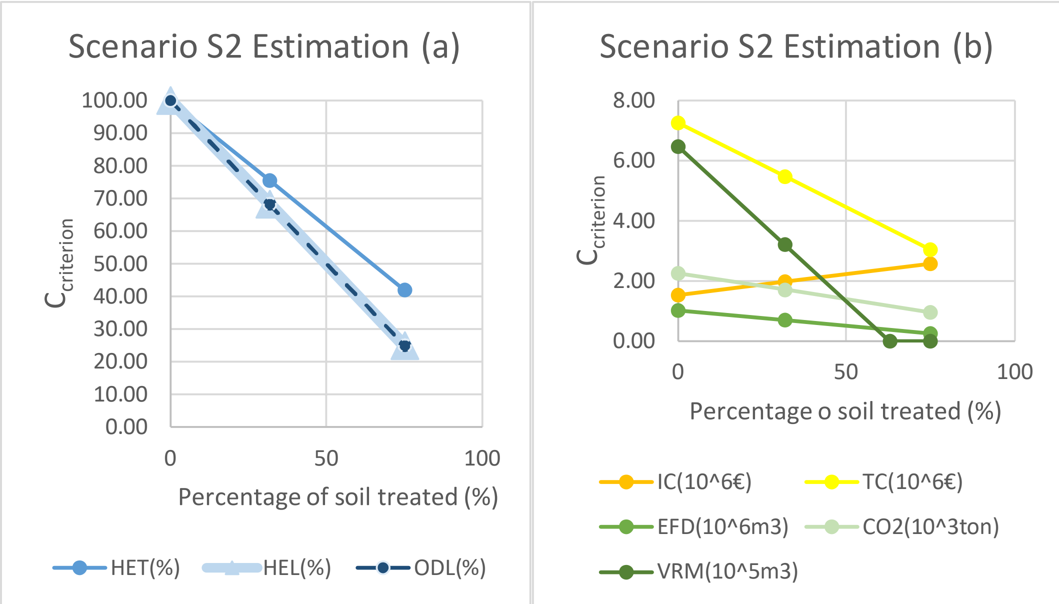

Figure 12. Scenario S2 estimation. (a) For criteria HET, HEL and ODL (b) For criteria IC, TC, EFD, CO2, VRM.

The need for virgin raw material represents a concrete amount and cannot be negative. Therefore, as mentioned earlier, the criterion was estimated so that it followed the linear regression up to the point that represented 99.9% reduction from scenario S0 and after that the value remained constant, namely $C_{VRM,S2}$ being equal to 0.1 % of $C_{VRM,S0}$. Table 10 shows all evaluations for all 3 scenarios.

Table 10. Scenarios S0, S1 and S2 evaluation. (* TS - Percentage of soil treated)

Criteria		Scenario S0	Scenario S1	Scenario S2
IC	€	1 541 280	1 979 380	2 576 599
TC	€	7 260 633	5 480 382	3 053 541
HET	%	100	75	42
HEL	%	100	68	25
ODL	%	100	68	25
EFD	m3	1027520	701 420	256 880
CO2	t	2 265	1 710	953
VRM	m3	646 834	320 734	647
TS*	%	0	32	75

4.4 Marginal Utility Contribution Calculation

Marginal utility contributions are used to avoid scale problems. At first, the data was transformed so that the scenarios with best performance had higher marginal utility scores. Afterwards, the values were normalized so that the sum of the marginal utility scores of all three scenarios is always one, for every criterion.

Table 11 summarizes the extreme values for the different criteria and the shape of the function. The shape was labelled as "Increasing" when the best value was higher than the worst as shown in in the table below. On the other hand, the cases had a "Decreasing" shape when the best value was lower than the worst. Figure 13a presents Health effects - transportation (HET) and Health Effects – Local (HEL) as examples of decreasing and increasing functions, respectively.

Table 11. Shape of value functions.

		Performance range		
Criteria	Unit	Worst	Best	Shape of value function
IC	€	2 576 598.56	1 541 280.00	↓ Decreasing
TC	€	7 260 633.00	3 053 541.22	↓ Decreasing
HET	%	100.00	42.06	↓ Decreasing
HEL	%	24.38	100.00	↑ Increasing
ODL	%	24.38	100.00	↑ Increasing
EFD	m3	1 027 520.00	256 880.00	↓ Decreasing
CO2	t	2 265.00	953.42	↓ Decreasing
VRM	m3	646 833.50	646.83	↓ Decreasing

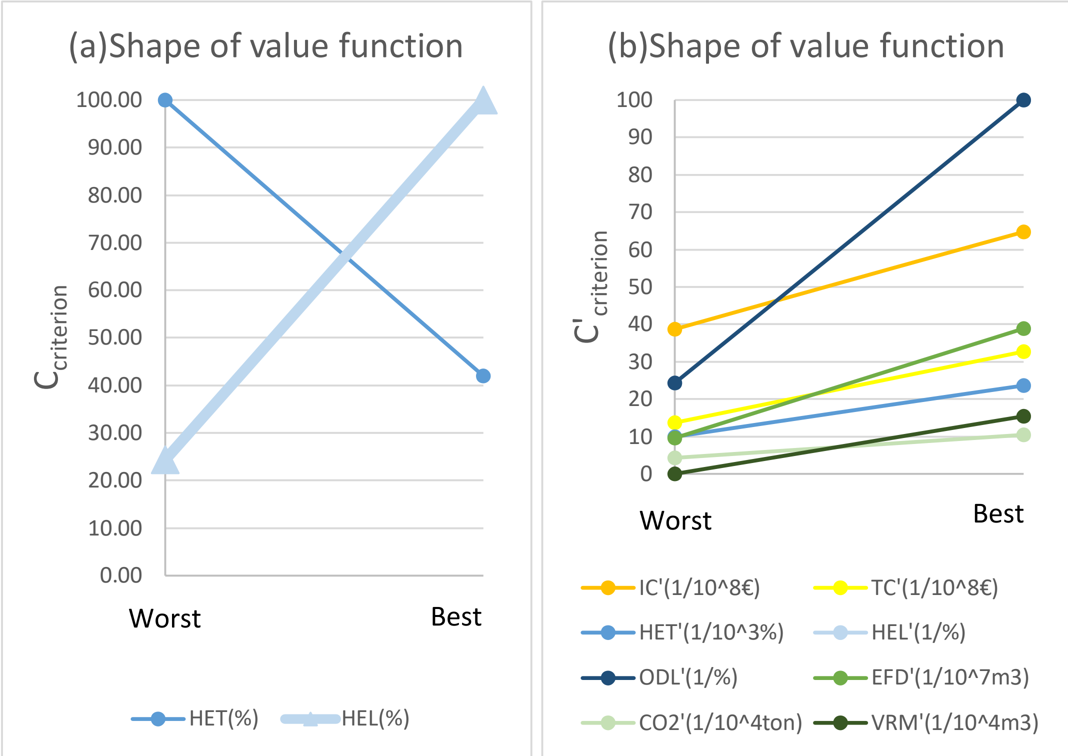

Figure 13. Graphic representation of the shape of the value functions. (a) For criteria HET and HEL before shape transformation. (b) For all criteria after shape transformation.

To start ranking the different scenarios the criteria that had a decreasing shape had their values inverted so that better performances obtained higher points. Increasing shape functions did not have to be altered, therefore the performance values ($C'_{criteria,scenario}$) were calculated following Equation 3.

$$C'_{criteria,scenario} = \begin{cases} C_{criteria,scenario}, & for\ criteria\ with\ increasing\ shape \\ & (HEL, ODL); \\ 1/C_{criteria,scenario}, & for\ criteria\ with\ increasing\ shape \\ & (IC, TC, HET, EFD, CO2, VRM) \end{cases} \quad (3)$$

Figure 13b shows the result of the above-mentioned transformation. After that, all the functions had an increasing shape, as seen in Table 12, and consequently best results were converted into more points to the respective scenario.

Table 12. Performances of scenarios S0, S1 and S2.

Criteria	S0	S1	S2	Worst	Best	Shape
IC	6.49E-07	5.05E-07	3.88E-07	3.88E-07	6.49E-07	↑
TC	1.38E-07	1.82E-07	3.27E-07	1.38E-07	3.27E-07	↑
HET	1.00E-02	1.32E-02	2.38E-02	0.010	0.024	↑
HEL	100.00	68.00	24.38	24.38	100.00	↑
ODL	100.00	68.00	24.38	24.38	100.00	↑
EFD	9.73E-07	1.43E-06	3.89E-06	9.73E-07	3.89E-06	↑
CO2	4.42E-04	5.85E-04	1.05E-03	4.42E-04	1.05E-03	↑
VRM	1.55E-06	3.12E-06	1.55E-03	1.55E-06	1.55E-03	↑

Next step was to normalize the values to obtain the marginal utility contribution ($C''_{criterion,scenario}$) for all scenarios according to each criterion. Before this change, the values used to compare different criteria had different scales, these values were normalized to enable adding the performances of all the criteria to obtain a final scoring.

To normalize, all the values were divided by the sum of all the values for the same criterion for all the scenarios as in Equation 4. The outcome of normalization is compiled in Table 13.

$$C''_{criterion,Scenario} = \frac{C'_{criterion,scenario}}{[C'_{criterion,S0}+C'_{criterion,S1}+C'_{criterion,S2}]} \qquad (4)$$

Table 13. Marginal utility contribution of scenarios S0, S1 and S2.

Criteria	S0	S1	S2
IC	0.42	0.33	0.25
TC	0.21	0.28	0.51
HET	0.21	0.28	0.51
HEL	0.52	0.35	0.13
ODL	0.52	0.35	0.13
EFD	0.15	0.23	0.62
CO2	0.21	0.28	0.51
VRM	0.00	0.00	1.00
Total	2.25	2.11	3.64

4.5 Utility Scores Function

In this study the utility function ($U_{scenario}$) applied was of the additive model. The weights were obtained from the questionnaire as shown in Equation 5.

$$U_{Scenario} = w_{IC}C''_{IC,scenario} + w_{TC}C''_{TC,scenario} + w_{HET}C''_{HET,scenario} + w_{HEL}C''_{HEL,scenario} + w_{ODL}C''_{ODL,scenario} + w_{EFD}C''_{EFD,scenario} + w_{CO2}C''_{CO2,scenario} + w_{VRM}C''_{VRM,scenario} \qquad (5)$$

The questionnaire (Appendix A) was developed to obtain the opinion of different stakeholders about the different criteria used to compare the possible scenarios.

The questionnaire was sent to a total of 30 interviewees, which included professionals from Espoo City Planning department, consulting and construction companies, as well as university professors from the Helsinki Region and also chairmen and vice chairmen from Espoo City's committees.

The questionnaire was sent by email and filled on-line using webropolsurveys between 05.10.2020 and 06.11.2020.

The interviewees were asked to give points to the criteria according to their view of importance. First, they gave 100 points to the criterion they considered the most important. Next, they decided which was the second most important and gave between 0-99 points comparing its importance with the first criterion chosen. Accordingly, they chose the most important criterion among the remaining criteria and gave points until all criteria had been filled.

A percentual distribution of points was calculated for every interviewee as shown in the example for the answers received from interviewee 1 in Figure 14a. To obtain the values to be used as weights in the final analysis, the average of the percentual share from all the answers was calculated for every criterion, and the final points distribution are shown in Figure 14b.

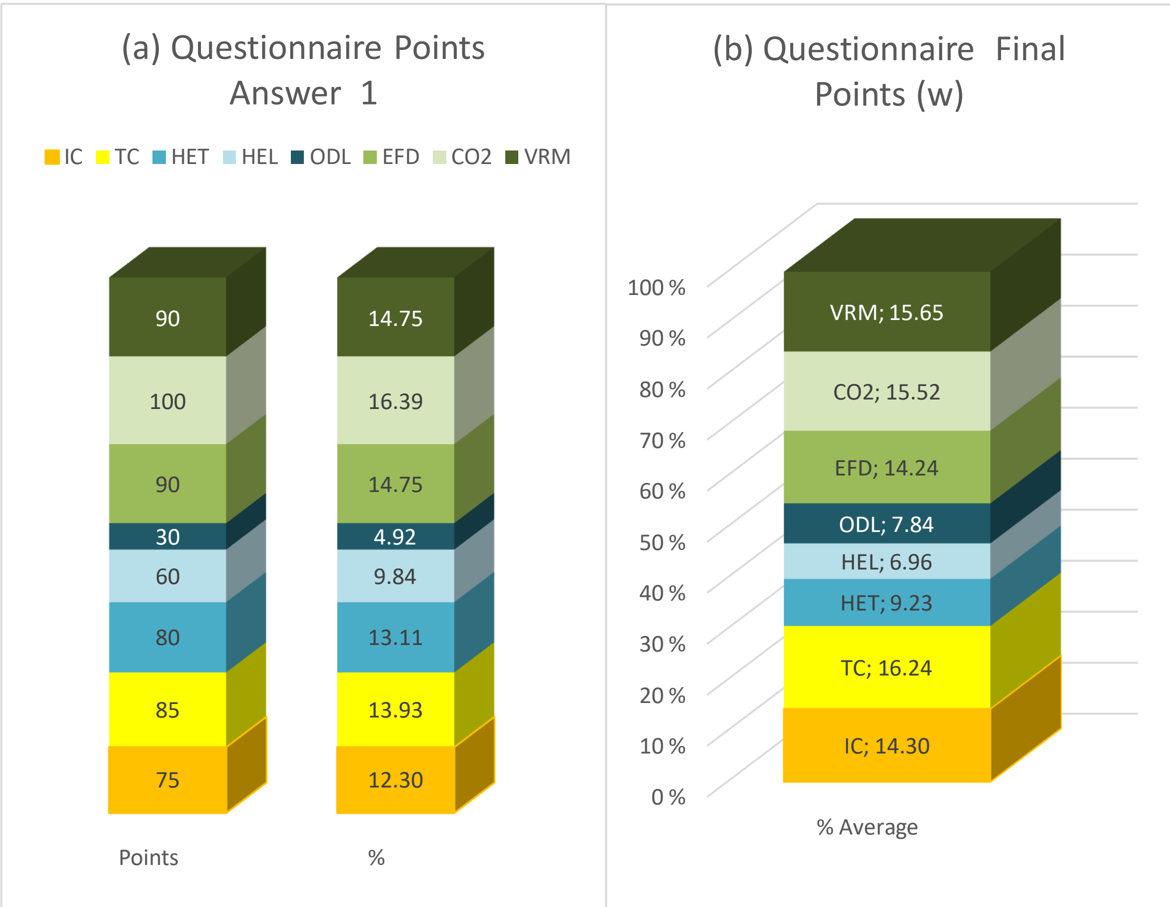

Figure 14. Questionnaire points distribution example and average values.

4.6 Scenarios' Utility Scores Calculation

The scores, listed in Table 14, were calculated using the Utility scores function presented in Equation 5. The questionnaire final points were obtained from Figure 14b and used as weights. The respective marginal utility contributions were collected from Table 13 for the different scenarios.

Table 14. Utility Score calculation.

	$w_{criterion}$	$C''_{criterion,S0}$	$C''_{criterion,S1}$	$C''_{criterion,S2}$	S0	S1	S2
IC	14.30	0.42	0.33	0.25	6.01	4.72	3.58
TC	16.24	0.21	0.28	0.51	3.41	4.55	8.28
HET	9.23	0.21	0.28	0.51	1.94	2.58	4.71
HEL	6.96	0.52	0.35	0.13	3.62	2.44	0.90
ODL	7.84	0.52	0.35	0.13	4.08	2.74	1.02
EFD	14.24	0.15	0.23	0.62	2.14	3.28	8.83
CO2	15.52	0.21	0.28	0.51	3.26	4.35	7.92
VRM	15.65	0.00	0.00	1.00	0.00	0.00	15.65
$U_{scenario}$					24.46	24.66	50.89

Balanced scores were calculated using the respective normalized performance and weights used to balance the impact of the criteria representing economic, social and environmental aspects to compensate for the fact that there were only two criteria illustrating economics aspects. The balanced weights were calculated using Equation 6 and their respective scores are listed in Table 15.

$$w_{B,criterion} = \begin{cases} (8/3)/2\, w_{criterion}\,, & for\ IC, TC \\ (8/3)/3\, w_{criterion}\,, & for\ other\ criteria\ but\ IC, TC \end{cases} \qquad (6)$$

Table 15. Balanced scores calculation.

	Aspects	$w_{criterion}$	$w_{B,criterion}$	S0	S1	S2
IC	Economic (8/3)/2	14.30	19.07	6.01	4.72	3.58
TC		16.24	21.65	3.41	4.55	8.28
HET	Social (8/3)/3	9.23	8.20	1.94	2.58	4.71
HEL		6.96	6.19	3.62	2.44	0.90
ODL		7.84	6.97	4.08	2.74	1.02
EFD	Environmental (8/3)/3	14.24	12.66	2.14	3.28	8.83
CO2		15.52	13.80	3.26	4.35	7.92
VRM		15.65	13.91	0.00	0.00	15.65
$U_{B,scenario}$				24.46	24.66	50.89

4.7 Sensitivity Analysis

Sensitivity analysis is the computation of the effect of changes in input values or assumptions and it can be conducted in different ways depending on the goal of the analysis, namely the sensitivity question. In this case the objective was to find out which criteria and its variation could have a strong effect on the result. (Borgonovo, 2017)

Marginal utility contribution varies between 0 and 1. Initially, the impacts of varying the values of the marginal utility contribution ($C''_{criterion,S0}$) to the extreme values were analyzed for the base scenario S0. Equations 7 and 8 show the example of the calculations for the criterion IC. Next, the difference between the total points of the extreme values and the respective original utility score were calculated according to Equations 9 and 10. The outcomes are listed in Table 16.

$$U_{IC,S0-} = w_{IC}0 + w_{TC}C''_{TC,S0} + w_{HET}C''_{HET,S0} + w_{HEL}C''_{HEL,S0} + w_{ODL}C''_{ODL,S0} + w_{EFD}C''_{EFD,S0} + w_{CO2}C''_{CO2,S0} + w_{VRM}C''_{VRM,S0} \quad (7)$$

$$U_{IC,S0+} = w_{IC}1 + w_{TC}C''_{TC,S0} + w_{HET}C''_{HET,S0} + w_{HEL}C''_{HEL,S0} + w_{ODL}C''_{ODL,S0} + w_{EFD}C''_{EFD,S0} + w_{CO2}C''_{CO2,S0} + w_{VRM}C''_{VRM,S0} \quad (8)$$

$$D^{-} = U_{S0-} - U_{S0} \quad (9)$$

$$D^{+} = U_{S0+} - U_{S0} \quad (10)$$

Table 16. Sensitivity analysis values for scenario base S0.

	U_{S0-}	U_{S0}	U_{S0+}	D-	D+
IC''	18.45	24.46	32.75	-6.01	8.29
TC''	21.05	24.46	37.29	-3.41	12.83
HET''	22.52	24.46	31.75	-1.94	7.29
HEL''	20.84	24.46	27.80	-3.62	3.34
ODL''	20.38	24.46	28.22	-4.08	3.76
EFD''	22.32	24.46	36.56	-2.14	12.10
CO2''	21.20	24.46	36.72	-3.26	12.26
VRM''	24.46	24.46	40.11	0.00	15.65

Next, same steps were repeated for scenarios S1 and S2 and the outcomes are collected in Figure 15. The light grey column shows the MCDA calculated utility score (U_{S0}) and the error bars show the performance with the marginal utility contribution ($C''_{criterion,S0}$) being substituted for 0 ($U_{criterion,So-}$) or 1 ($U_{criterion,So+}$).

Scenarios S0 and S1 were calculated the same way and using the same assumptions, therefore inaccuracies in the estimations are expected to be similar. Scenario S2 was estimated differently, hence its fluctuation and relation to the other two was specially observed. Figure 15 shows that the fluctuations impacts had similar behavior for most criteria.

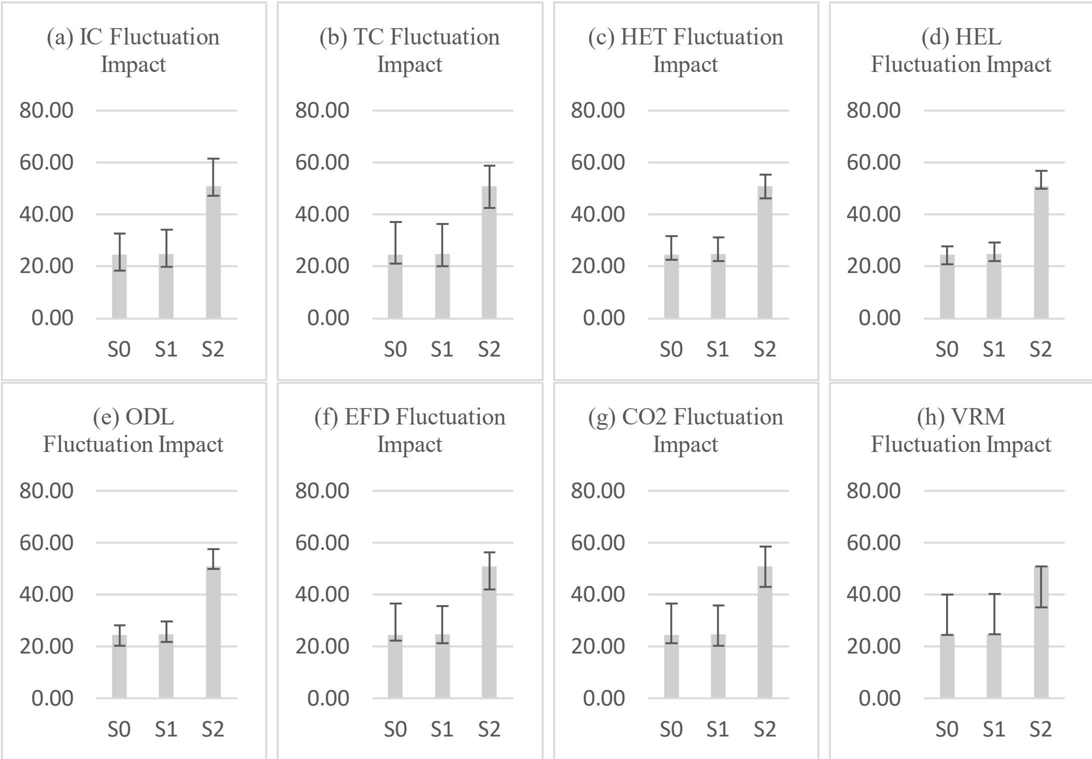

Figure 15. Sensitivity analysis for all three scenarios according to different criteria with vertical axes measuring the utility score and the variations from the sensitivity analysis represented by the error bars.

For all the criteria, $U_{criterion,So-}$ and $U_{criterion,S0+}$ have similar values to $U_{criterion,S1-}$ and $U_{criterion,S1+}$ respectively. Moreover, $U_{criterion,S2-}$ is higher than all the simulations made for scenarios S0 and S1 for almost all criteria. This means that variations in only one criterion would hardly change the proportions between the utility score of the scenarios S0, S1 and S2. However, in Figure 15h, where the lowest extreme for scenario S2 is lower than the higher extremes for scenarios S1 and S2 ($U_{VRM,S2-} < U_{VRM,S0+}$) and ($U_{VRM,S2-} < U_{VRM,S1+}$). Therefore, it was further analyzed, using Equations 11 and 12, what would happen to scenarios S0 and S1 in the case of the scenario S2 receiving the lowest value possible for the criterion VRM.

$$U_{VRM,S2-,S2} = w_{IC}C''_{IC,S2} + w_{TC}C''_{TC,S2} + w_{HET}C''_{HET,S2} + w_{HEL}C''_{HEL,S2} + w_{ODL}C''_{ODL,S2} + w_{EFD}C''_{EFD,S2}w_{CO2}C''_{CO2,S2} + w_{VRM}0 \quad (11)$$

Assuming that the ratio between the marginal utility contributions follows the ratio of the initial evaluations, $C''_{VRM,S1}$is twice the value of $C''_{VRM,S0}$. Normalization process guarantees that the sum of marginal utility contributions of all three scenarios.

In the analysis of the $U_{VRM,S2-}$, the Equations 12 and 13 lead to the values $U_{VRM,S2-,S0}$=29.62 and $U_{VRM,S2-,S1}$= 35.15

$$C''_{VRM,S1}/C''_{VRM,S0} = 2 \quad (12)$$

$$C''_{VRM,S0} + C''_{VRM,S0} + 0 = 1 \quad (13)$$

5 Results and Discussion

The main goal was to find out the best approach to handle excavated soil and rock in the city of Espoo. As described in Section 1, the first option named scenario S0 referred to continuation of current procedure without centralized follow-up of the exchange and reuse. Scenario S1 referred to investments for the establishment of two temporary deposits enabling improving the reuse of gravel and high bearing capacity soil. In scenario S2 the investment seeks to recycle 75% of all the excavated soil, and therefore implement more temporary deposits and/or new technologies to enable the reuse of all the excavated material.

5.1 Questionnaire

A total of 15 answers were received in the questionnaires and results are summarized in Figure 16. Figure 16a shows the distribution of points obtained from the questionnaire. The criteria with the highest average points were Transportation costs, CO_2 emissions and Virgin raw material demand with an average over 80 points. The next criteria in the ranking were Investment costs and Disposal of earth masses with slightly over 70 points. On the other extreme, the social aspects of Health effects from transportation, Health effects local and Other disturbance local received in average less than 50 points.

The difference between social and the other two aspects became visible when the results were combined according to their type. The social aspects criteria had an average of 42 points, whereas the economic and environmental aspects had 77 and 79 points, respectively. Figure 16b shows a different way to combine the criteria by visualizing how the points in each questionnaire were divided by the three types. Most points in most questionnaires were given to environmental criteria and social and economic criteria remained mainly oscillating between the second and third places.

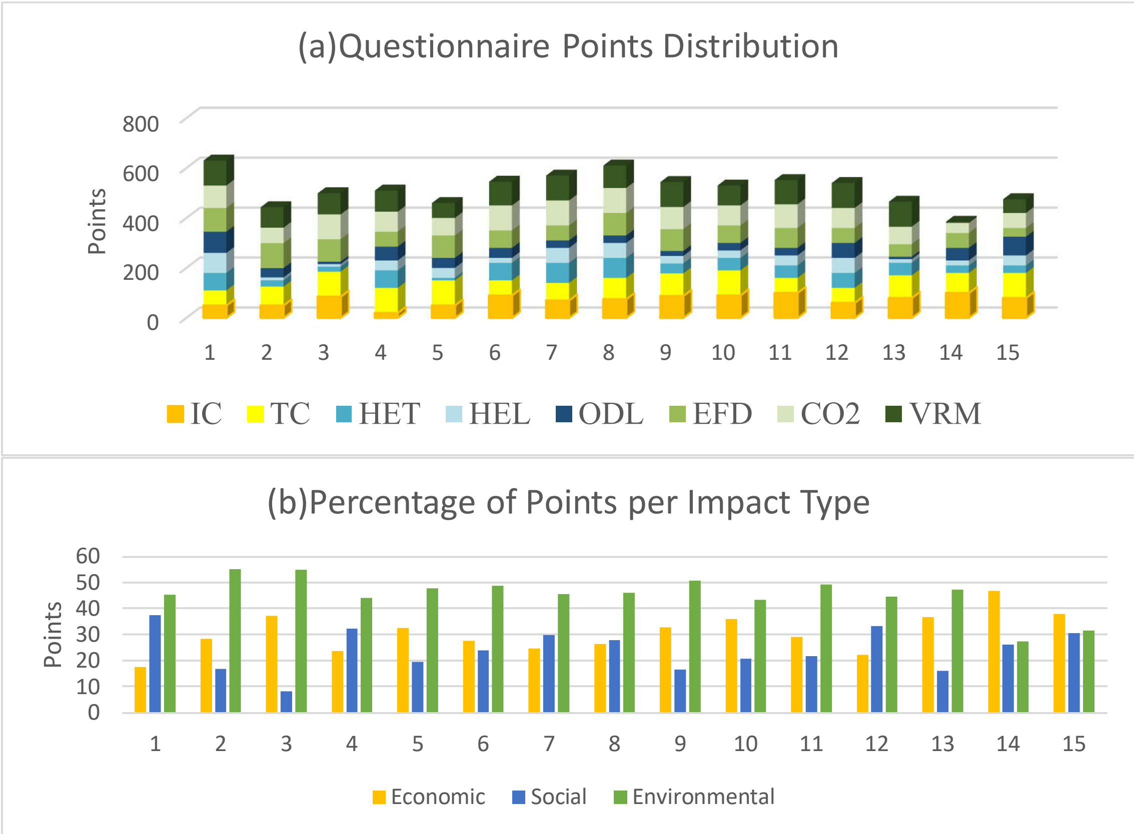

Figure 16. Questionnaire answers and point distributions according to impact type.

Marttunen (2011) reinforced that beyond enabling to reach for an agreement on criteria weights, as done in this study, MCDA helps people involved to become more conscious on interests and preferences of other stakeholders, as well as prepared to accept and understand different views. Therefore, MCDA increases the stakeholders' commitment to the process and final decision.

5.2 Scenarios Analysis

Figure 17 shows the final scores for the three scenarios according to the calculated utility scores from Table 14. The figure reveals the role of every criterion for the performance of the scenarios. The environmental impacts criteria had a strong influence on the high score of scenario S2, and the transportation costs also had a significant role. Scenarios S0 and S1 had similar distributions, with the values of investment and transportation costs counterbalancing each other. In a similar manner the scenario S0 received more points from social aspects and scenario S1 from environmental aspects. The final score was consequently quite similar for these two scenarios, as U_{S0} was 24.46 and U_{S1} was 24.66. These values were much lower than scenario S2 with U_{S2} value of 50.89.

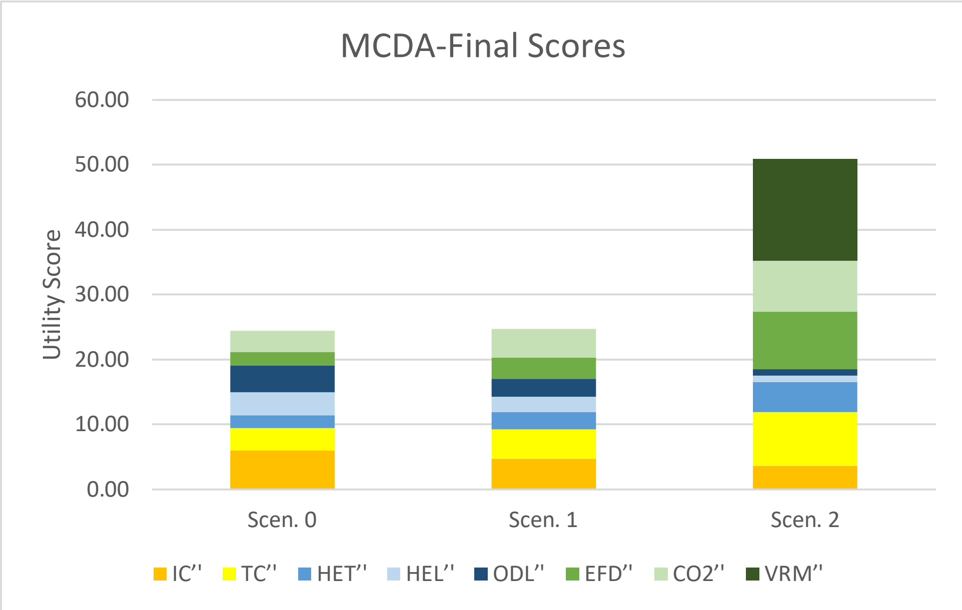

Figure 17. MCDA final scores for scenarios S0, S1 and S2.

The high average score for the economic aspects criteria (Figure 17) was not accurately reflected on its impact on the final result, because in the questionnaire there was only two criteria of this type and three of the other two. As explained in the calculations new scores were calculated using an intermediate weight to balance the impact.

The comparison of the results presented in Figure 17 with the balanced scores from Table 15 is presented in Figure 18. There was a minor rise in the scores of scenarios S0 and S1 and a small contraction on the score of the scenario S2. But the main proportions remained similar, scenario S1 being slightly higher than scenario S0 and scenario S2 significantly higher than the other two.

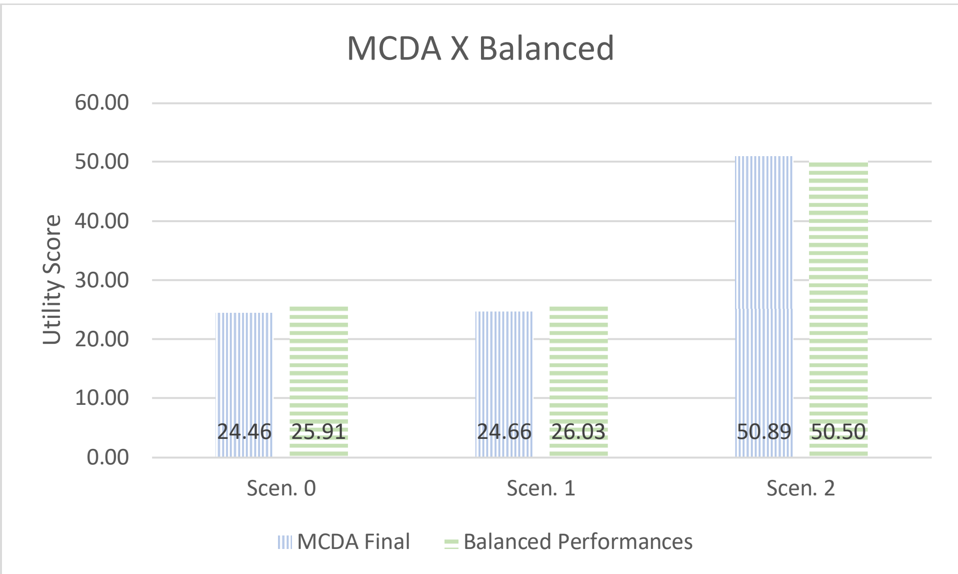

Figure 18. Comparison between MCDA and Balanced final scores.

In the balanced calculation, the existence of a third criterion representing economic aspects was simulated. This criterion received points in a similar range to the other two criteria (TC, IC) representing economic aspects. The balanced situation is unlikely to happen, once the criteria were chosen to the questionnaire based on the impacts most cited during the initial phase of the study. The scores of the third economic criterion would likely be between the non-existence of this criterion (score 0) and the average value used in the balanced study. Therefore, the final result would probably stay between the two possibilities shown in Figure 18 and also keep the same proportions.

As stated by Marttunen (2011) it is not easy to assess the effect of MCDA on reaching agreement. But MCDA has innumerous components that improved in his study the quality of the planning and decision-making process. He also noted that MCDA methods can be an important support on decision-making in management and policy levels. Despite the risk of being laborious, MCDA approach is interactive and integrated, and it can help the identification of the most significant impacts in the early phases of planning. Mustajoki et al. (2004) mentioned the possibility to use modern computer technology to enable participation, for example, through on-line decision analysis interviews.

The current study also sought to demonstrate the possibility of integrating MCDA concepts in the management and policy levels for the city of Espoo. MCDA can help the communication between technical departments, decision makers and city committees, facilitating their participation and understanding of the decisions made.

Figure 17 shows that scenario S2 had significantly higher utility score than the other two alternatives and, consequently, is the best option for the city of Espoo. Furthermore, scenario S2 becomes even stronger if we take into consideration the fact that according to OSF (n.d) the population of Finland is expected to start decreasing in 2031 and in 2050 the population would already have 100 000 less inhabitants than today. (YM, 2021)

Hiete et al. (2011) argued that population decreases in industrialized countries until 2050 are going to affect both demolition and new construction activities. Such changes would be challenging even for areas that already have high recycling rates, like the Federal state of Baden Württemberg in Germany that recycles around 79% of excavated material, which is close to the percentage targeted in scenario S2. Hiete et al. (2011) also noticed that disposal taxes are a cost-effective political instrument but would increase the share of low-quality recycling. On the other hand, investing on the acceptance and demand of high-quality recycling products would be a better option to handle the expected increases of C&D waste caused by population decline. (Magnusson et al., 2015)

Achillas et al. (2013) listed five other studies where MCDA was used to assist in construction and demolition waste management. In three of the cases, MCDA was used to seek an optimal waste management strategy, one of them to identify the optimal location for an inert landfill and the last one involves the implementation of a waste treatment facility. Differently from this study, the study mentioned in Achillas et al. (2013) mainly focused on establishing the optimal location.

5.3 Sensitivity Analysis

The first step of the sensitivity analysis was to analyze the impact of varying the value of the normalized performances between the interval of 0 and 1 for scenario S0. The results are listed in Table 16 and collected in the tornado chart in Figure 19. The highest impact was for the Virgin raw material criteria, as expected, once it had initially value 1. As showed in the calculations, this criterion also had the biggest impact in the other two scenarios (Figure 15h). The most important finding was that the studied variation in this criterion was the only one able to significantly change the proportions among the final scores.

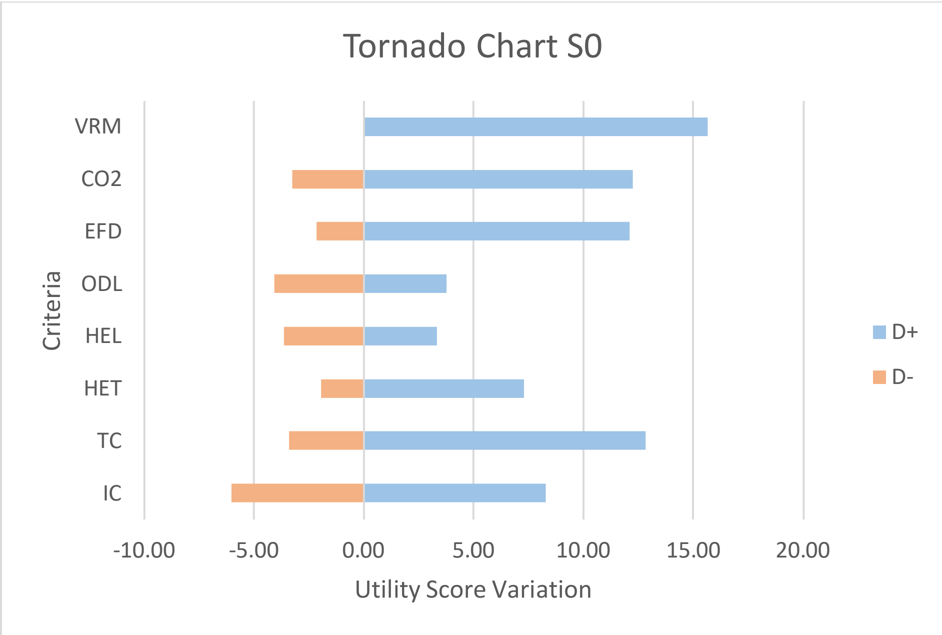

Figure 19. Tornado chart for base scenario S0 with the impacts of replacing the original marginal utility contribution for 0 (D-) and 1 (D+).

In the second phase, the simulations were made to detect the impact, of the marginal utility contribution for Virgin Raw Material in scenario S2 being zero, on the other two scenarios. Figure 20 shows that in this case the gap between the scenarios decreased. Scenarios S1 and S2 had quite similar scores and scenario S0 a bit lower score.

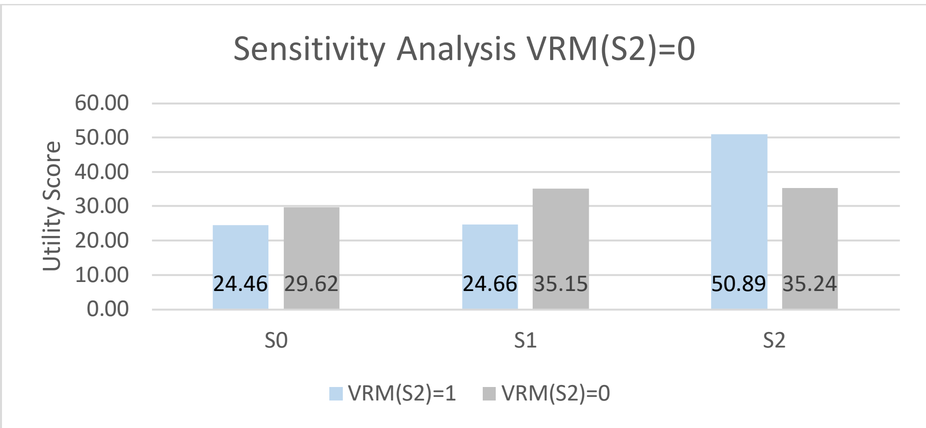

Figure 20. Comparison of MCDA scores with sensitivity analysis of criterion Virgin raw material demand with the following marginal utility contributions: $C''_{VRM,S0} = 0.33$; $C''_{VRM,S1} = 0{,}67$; $C''_{VRM,S2} = 0$.

Variations in the Virgin raw material demand criterion could only be the consequence of changes in the calculations of the amount of excavated soil and rock being landfilled or in the estimation of the current soil and rock demand. Magnusson et al. (2005) noted that it is challenging to find out the quantities of excavated soil and rock in urban regions from the literature. But they were able to establish a probable range of values for some flows, for example, the presented range of landfilling excavated soil and rock was 0.4 to 5.5 t/y/capita, while the value for the base scenario S0 was 7.1 t/y/capita. The S0 value is higher than the expected range from Magnusson et al. (2005), probably due to the metro construction during the period of the study. The use of quarry material on the other hand, was closer to the expected interval. The estimated value for S0 was 4.5 t/y/capita and the interval from Magnusson et al. (2005) was 4.6 to 8.0 t/y/capita. The current study also indicated that the reuse of soil and rock might achieve a reduction of up to 14 kg CO_2 per ton of material reused. The differences between scenarios S0 and S1 showed a reduction of 8.5 kg CO_2 per ton of material only from the CO_2 emissions coming from the material transportation. So, the values were quite close to the expected values and the large difference needed for this criterion to have an extremely low normalized performance is most likely not happening.

6 Conclusions

The main objective of this study was to define the best approach to manage excavated soil and rock in the city of Espoo. Initially, three alternative approaches were created: scenario S0 referred to the continuation of current practice without centralized follow-up of the exchange and reuse; scenario S1 referred to investments on the establishment of two temporary deposits enabling improved reuse of gravel and high bearing capacity soil; scenario S2 referred to the investment to recycle 75% of all the excavated soil. Scenario S2 would require the implementation of more temporary deposits and/or new technologies to enable the reuse of all the excavated material.

The participation of different stakeholders was facilitated by a questionnaire. The criteria with the highest average points were Transportation costs, CO2 emissions, and Virgin raw material demand with average over 80 points. On the other extreme, the social aspects of Health effects from transportation, Health effects local and Other disturbance local received in average less than 50 points.

There were only two criteria for the economic aspects, and therefore its high average score was not precisely reflected on its impact on the result. A simulation of a balanced study using an intermediate weight to balance the impact was made and the main proportions remained similar, scenario S1 slightly higher than Scenario S0 and scenario S2 significantly higher than the other two.

Based on the results of this study, the recommendation is that the city of Espoo should try to reproduce scenario S2. It was undoubtedly considered the best choice according to the alternatives and criteria used in this work. The result looked even stronger when the expected population decrease and the respective changes in the construction market were brought into the discussion. Scenarios S0 and S1 obtained similar scores, but scenario S1 had the advantage of possibly functioning as a more realistic intermediate step to achieving the conditions in scenario S2 in the future.

The twelve committees (mentioned in section 3) that try to bring a resident- and customer-oriented view, have an important role on the decision making in Espoo. Still, MCDA can be used as an alternative way to improve their participation and help the participants to understand different points of view.

Finally, the sensitivity analysis observed the impact of variation on the normalized performance of the criterion "Virgin raw material demand”, which was the only one with some possibility to bring changes to the proportions on the final scores. In the extreme case, scenarios S1 and S2 received quite similar scores and scenario S0 had a bit lower score. The comparison of the values used in the study and values obtained from literature indicated that it is unlikely that this criterion would behave like in the sensitivity analysis and changes in the inputs would most likely not have a big impact on the final result proportions.

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Appendix 1 - Questionnaire

Ylijäämämaamassojen Hallinta Espoossa

Respondent:
XXXXXXXXXXXX
Response on:
XX.XX.XXXX, XX:XX - XX.XX.XXXX, XX:XX

1. TärkeysluokkaVain (1) kriteeri/tärkeysluokka (TäyttöohjeetValitkaa Teidän mielestänne tärkein maamassojen hallintaan vaikuttava tekijä kohdassa tärkeysluokka, merkitkää se numerolla yksi ja antakaa sille 100 pistettä.Seuraavaksi valitkaa toiseksi tärkein vaikuttava tekijä ja merkitkää se tärkeysluokassa numerolla 2. Antakaa sille pisteet 0-99:n välistä riippuen siitä, kuinka tärkeä se mielestänne on ensimmäiseen vaikutukseen verrattuna. Tämän jälkeen toistakaa samat vaiheet kaikkiin kohtiin kunnes kaikilla luetelluilla vaikuttavilla tekijöillä on tärkeysluokka ja pisteet.Huomioikaa, että tärkein kysymys on, kuinka tärkeä vaikuttava tekijä on verrattuna muihin lueteltuihin kriteereihin. Jos mielestänne jotkut kriteerit eivät ole tärkeitä, voitte antaa niille nolla pistettä. Voitte myös ensin numeroida kriteerit mieleiseenne tärkeysjärjestykseen ja vasta sitten antaa pisteet.Kunkin vaikuttavan tekijän alla on painike i, jonka takaa löytyy lisää tietoa kriteeristä.)

	1	2	3	4	5	6	7	8
Investoinnin Kustannukset	○	○	○	○	○	◉	○	○
Kuljetuskustannukset	○	○	○	◉	○	○	○	○
Kuljetusten terveysvaikutukset	○	○	○	○	◉	○	○	○
Terveysvaikutukset (Paikallinen)	○	○	○	○	○	○	◉	○
Muut välivarastojen aiheuttamat häiriöt naapurustossa	○	○	○	○	○	○	○	◉
Maa-massojen läjitys suoraan loppusijoitukseen	○	○	◉	○	○	○	○	○
Kuljetuksista aiheutuvat päästöt (CO2)	◉	○	○	○	○	○	○	○
Neitsellisten raaka-aineiden tarve	○	◉	○	○	○	○	○	○

2. Pisteet(0-100) (TäyttöohjeetValitkaa Teidän mielestänne tärkein maamassojen hallintaan vaikuttava tekijä kohdassa tärkeysluokka, merkitkää se numerolla yksi ja antakaa sille 100 pistettä.Seuraavaksi valitkaa toiseksi tärkein vaikuttava tekijä ja merkitkää se tärkeysluokassa numerolla 2. Antakaa sille pisteet 0-99:n välistä riippuen siitä, kuinka tärkeä se mielestänne on ensimmäiseen vaikutukseen verrattuna. Tämän jälkeen toistakaa samat vaiheet kaikkiin kohtiin kunnes kaikilla luetelluilla vaikuttavilla tekijöillä on tärkeysluokka ja pisteet.Huomioikaa, että tärkein kysymys on, kuinka tärkeä vaikuttava tekijä on verrattuna muihin lueteltuihin kriteereihin. Jos mielestänne jotkut kriteerit eivät ole tärkeitä, voitte antaa niille nolla pistettä. Voitte myös ensin numeroida kriteerit mieleiseenne tärkeysjärjestykseen ja vasta sitten antaa pisteet.Kunkin vaikuttavan tekijän alla on painike i, jonka takaa löytyy lisää tietoa kriteeristä.)

Investoinnin Kustannukset	75
Kuljetuskustannukset	85
Kuljetusten terveysvaikutukset	80
Terveysvaikutukset (Paikallinen)	60
Muut välivarastojen aiheuttamat häiriöt naapurustossa	30
Maa-massojen läjitys suoraan loppusijoitukseen	90
Kuljetuksista aiheutuvat päästöt (CO2)	100
Neitsellisten raaka-aineiden tarve	90